The Signatures of Baryon Acoustic Oscillations and Primordial Non-gaussianities in the Lyman-alpha forest

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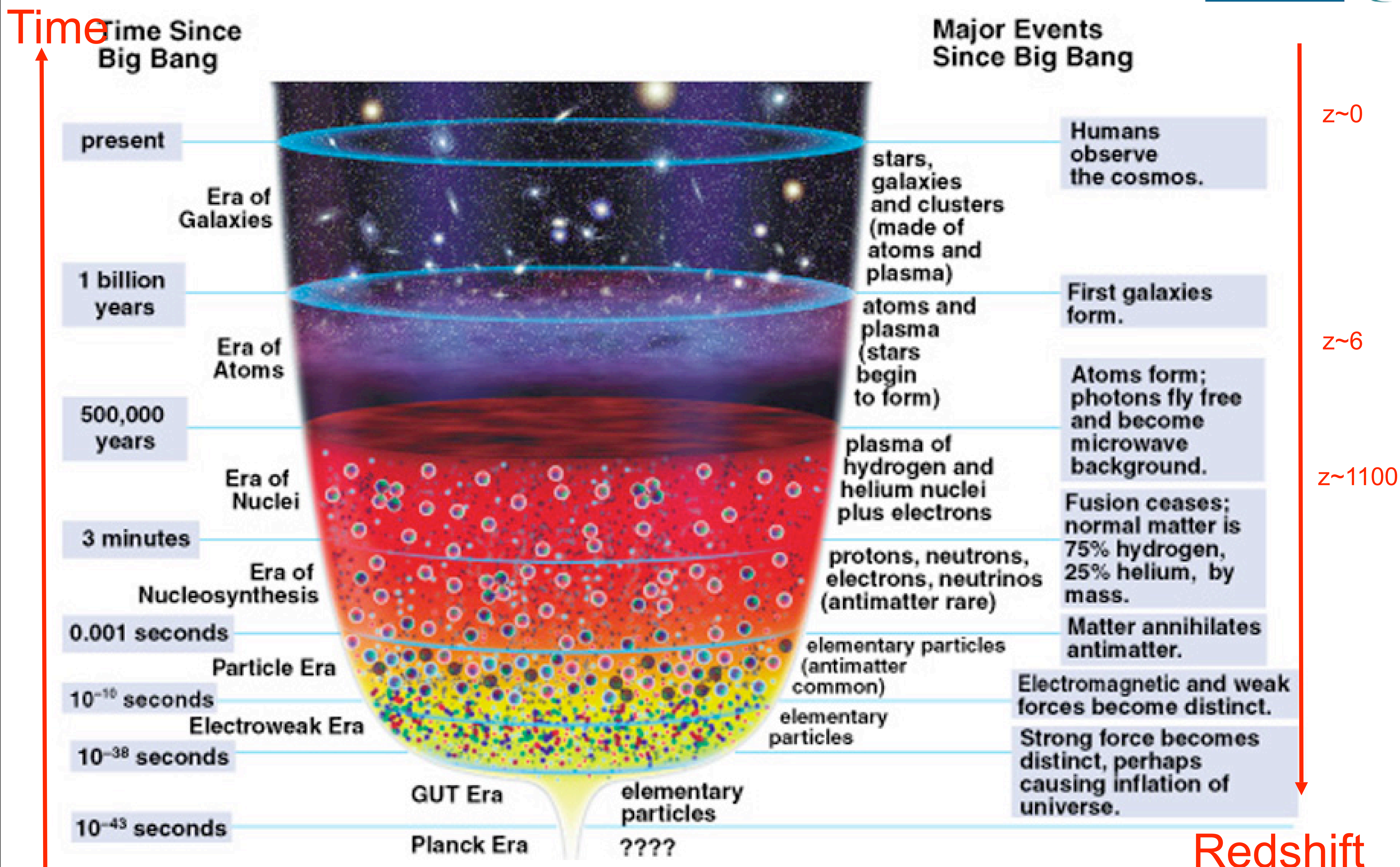
10/5/09, Fermilab

Outline

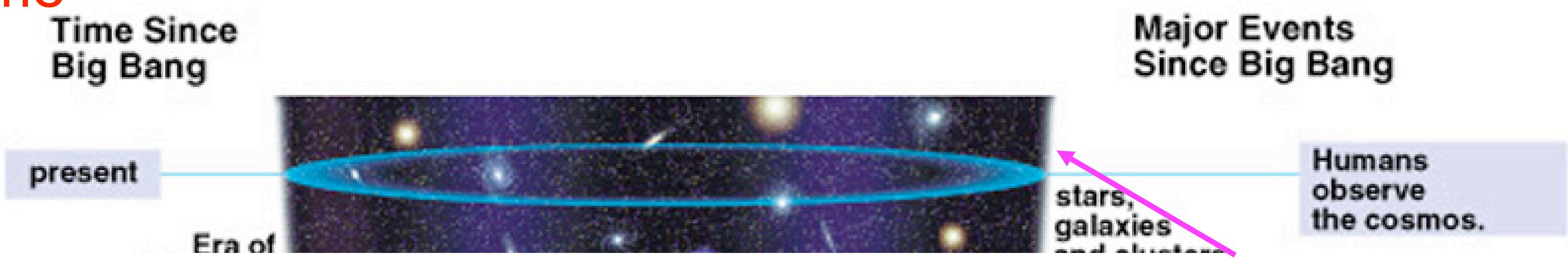
- Motivations
- Introduction (What is Lyman-alpha forest?)
- What can you do with Lyman-alpha forest?
  - —Baryon Acoustic Oscillations
    - Dark Energy
  - —Scale Dependent Bias
    - Primordial Non-gaussianities (f_nl)
- Conclusion

Motivations



Motivations

Time



Gravity +
observing movement of
local galaxies ->
"Dark Matter"

z~0

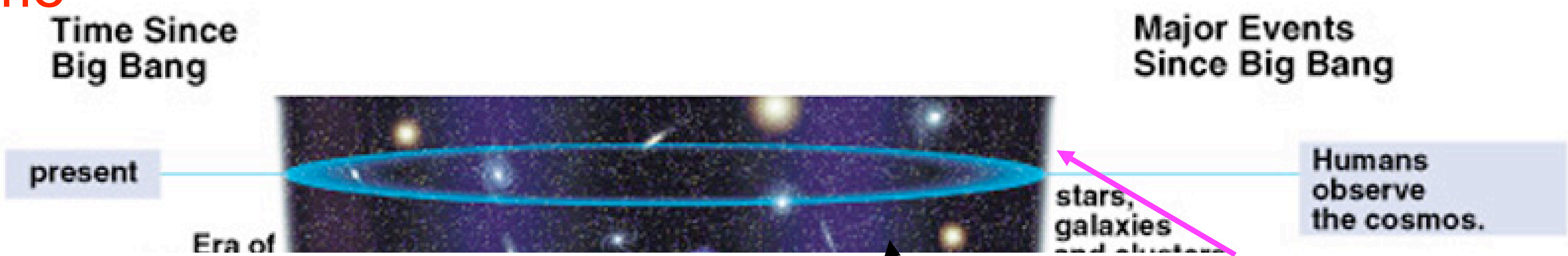
z~6

z~1100

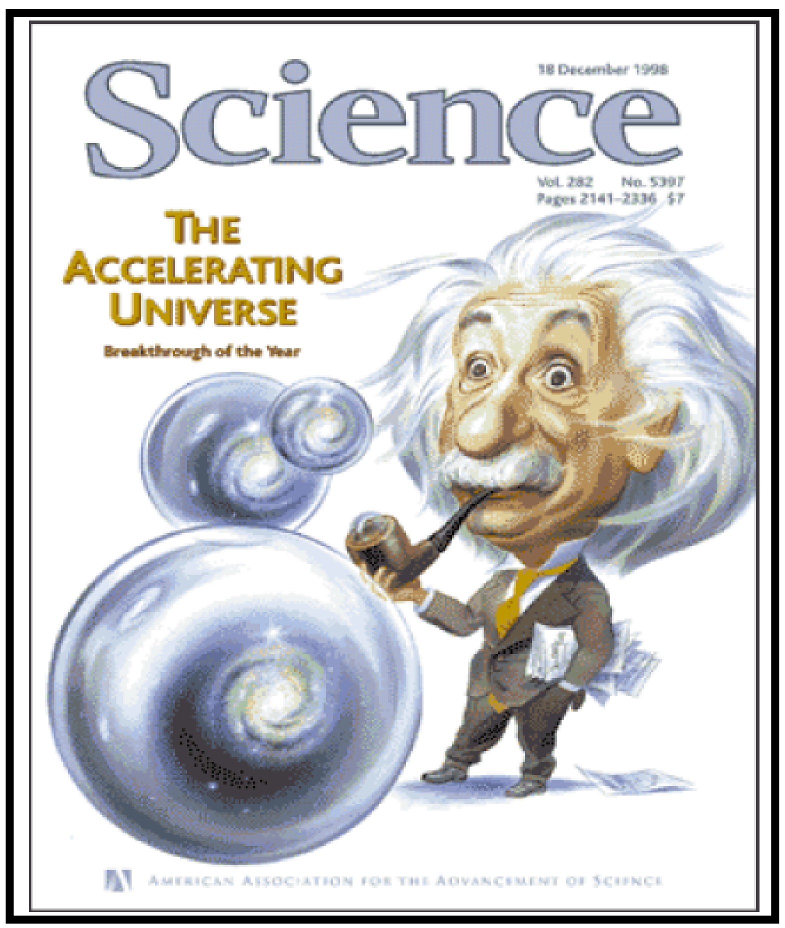
Redshift

Motivations

Time



Gravity + observing movement of local galaxies -> "Dark Matter"



Distant supernovas appear fainter than expected (1998)-> Universe is accelerating -> Cosmological Constant? Dark Energy?

z~0

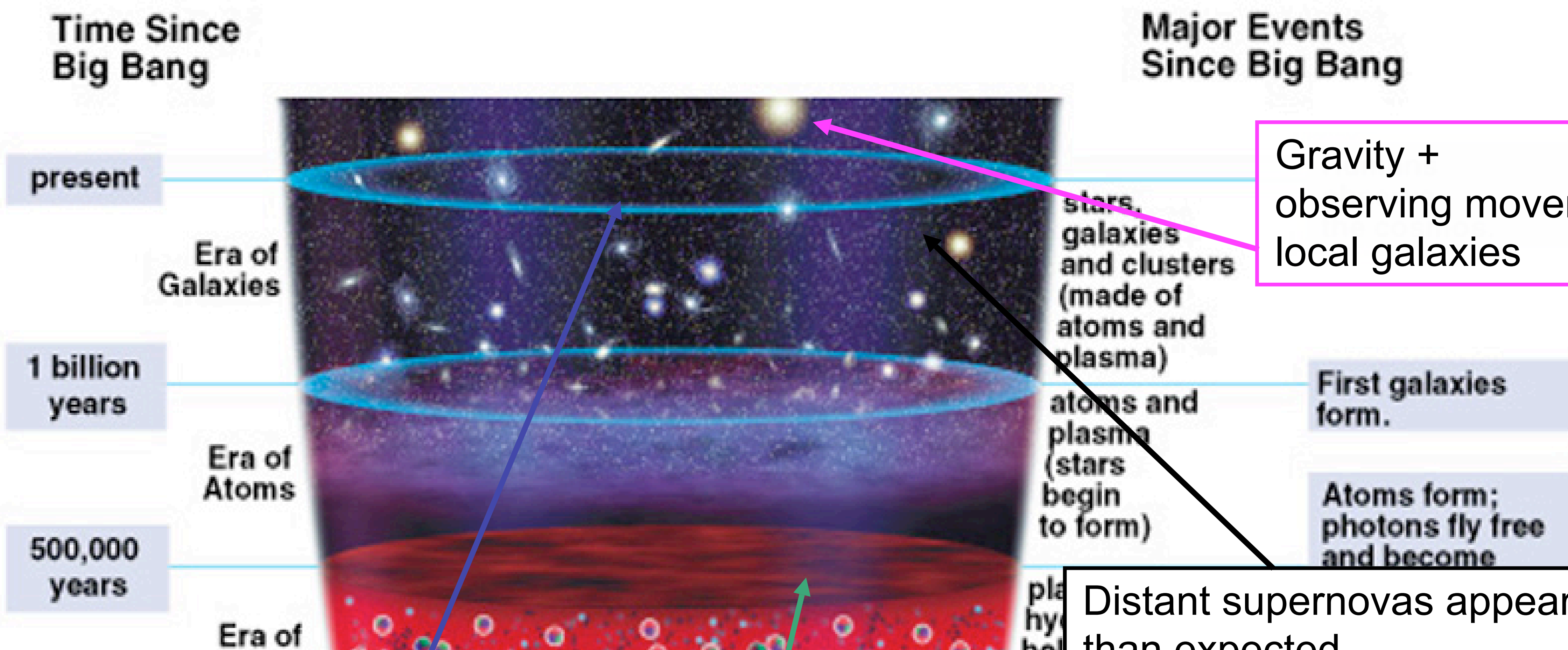
z~6

z~1100

Redshift

Motivations

Time



z~0

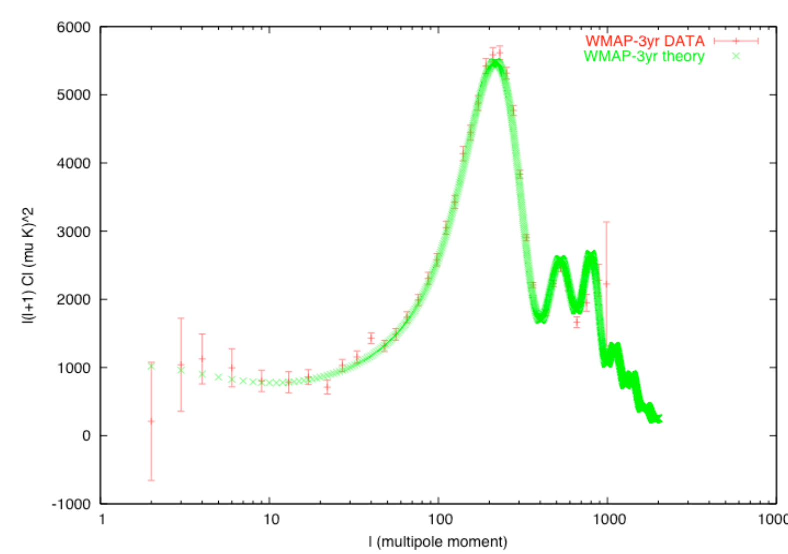
Gravity + observing movement of local galaxies

z~6

~1100

Distant supernovas appear fainter than expected

Observations of how galaxies cluster



Observations of
Cosmic Microwave Background (CMB)
-> angular powerspectrum of
temperature anisotropies

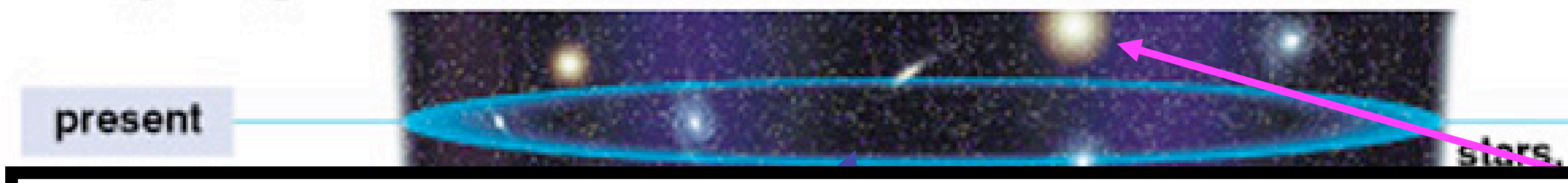
Redshift

Motivations

Time

Time Since Big Bang

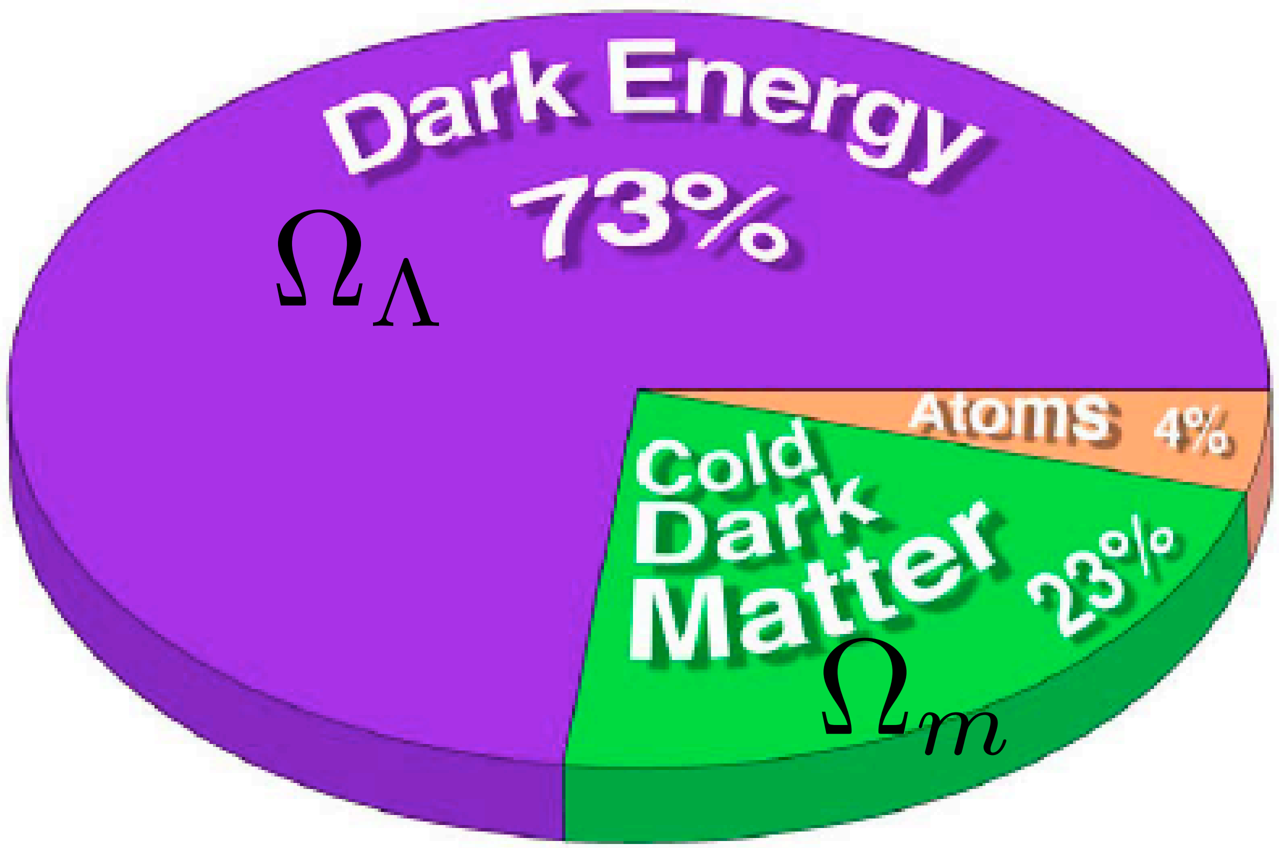
Major Events Since Big Bang

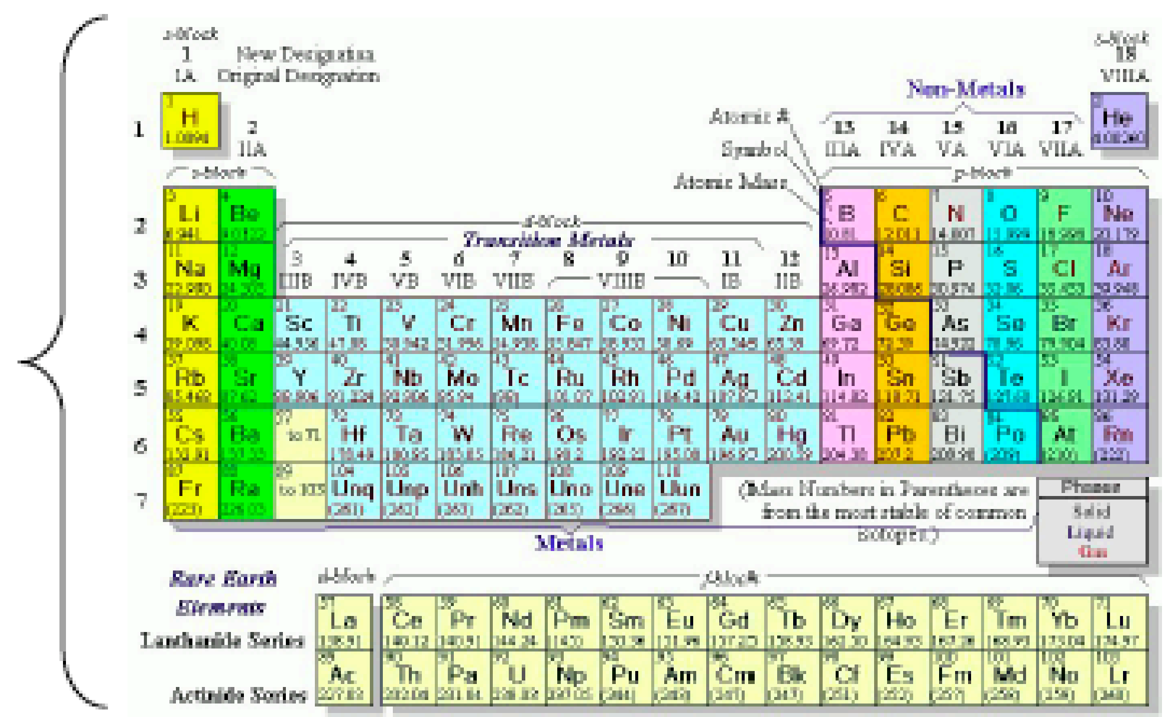


z~0

Gravity + observing movement of

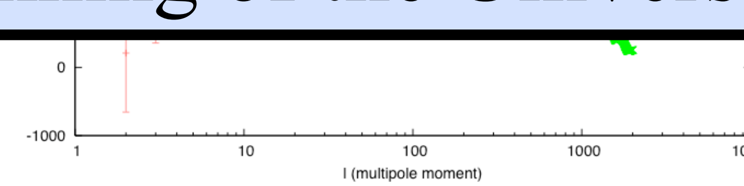
100





What happened at the Beginning of the Universe?

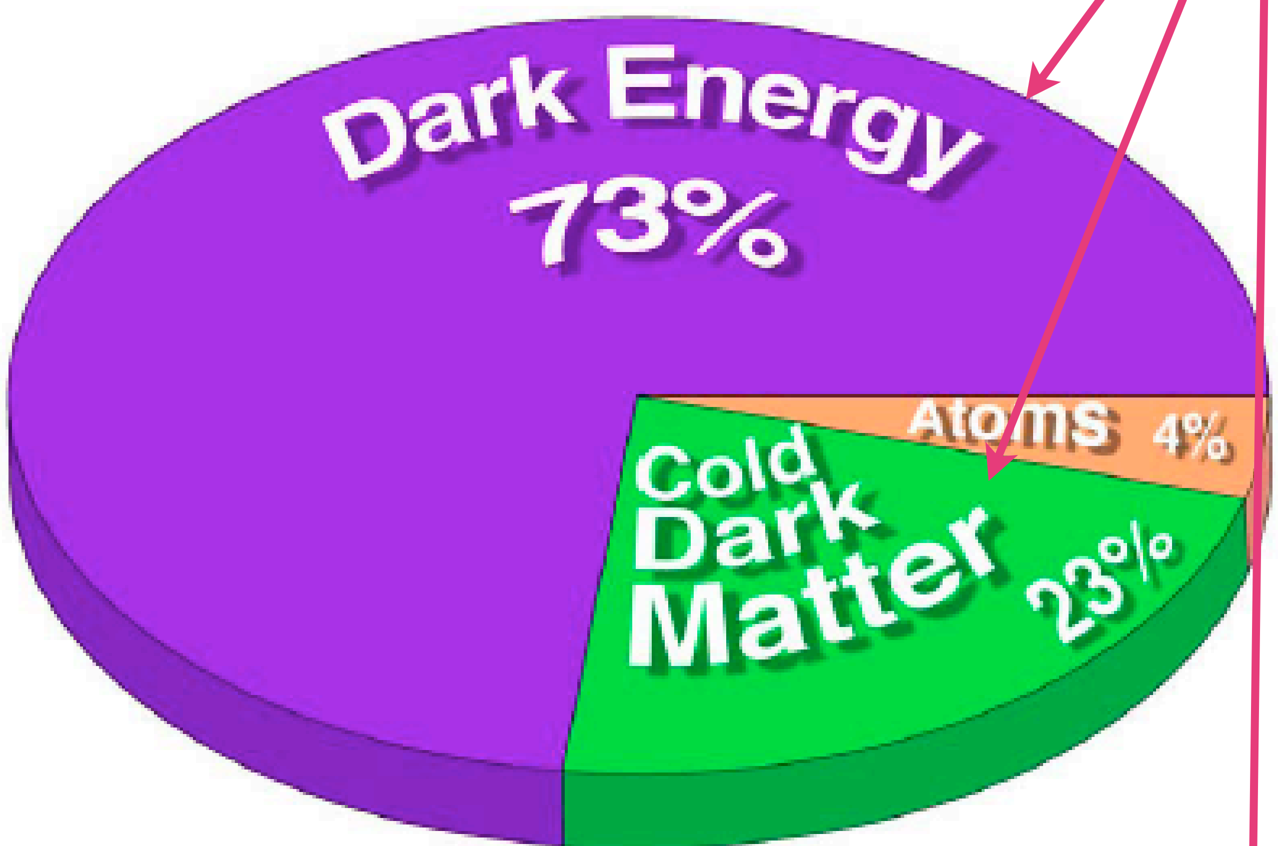
-> angular powerspectrum of temperature anisotropies

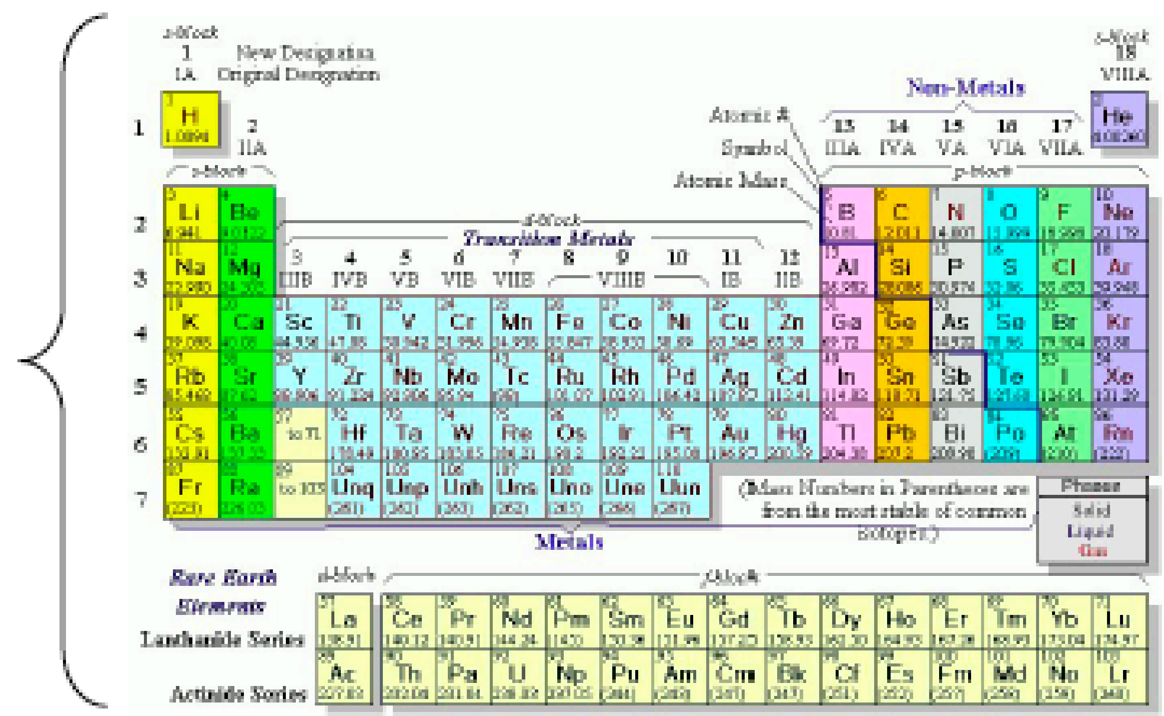


Redshift

Motivations

??





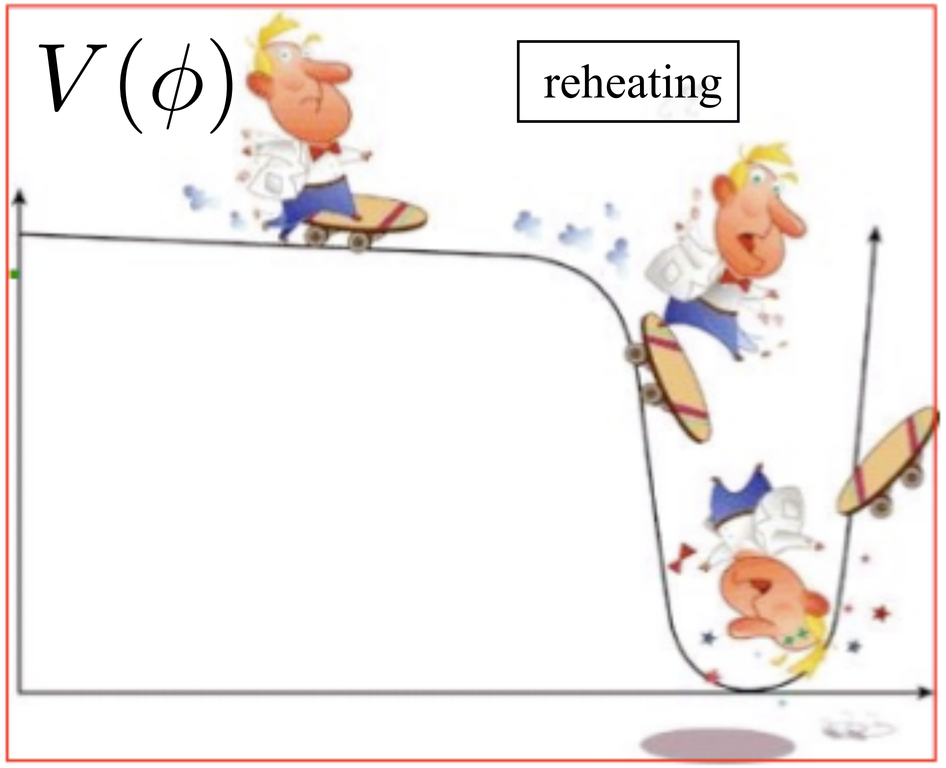
What happened at the Beginning of the Universe?

Lyman Alpha Forest: what can it do?
—Non-gaussianities in Early Universe

parameterize how much non-linear corrections are there to the potential

$$\Phi = \phi + f_{NL}\phi^2$$

Primordial potential (assumed to be gaussian random field)



Inflation

Lyman Alpha Forest: what can it do?
—Non-gaussianities in Early Universe

parameterize how much non-linear corrections are there to the potential

$$\Phi = \phi + f_{NL}\phi^2$$

Primordial potential (assumed to be gaussian random field)

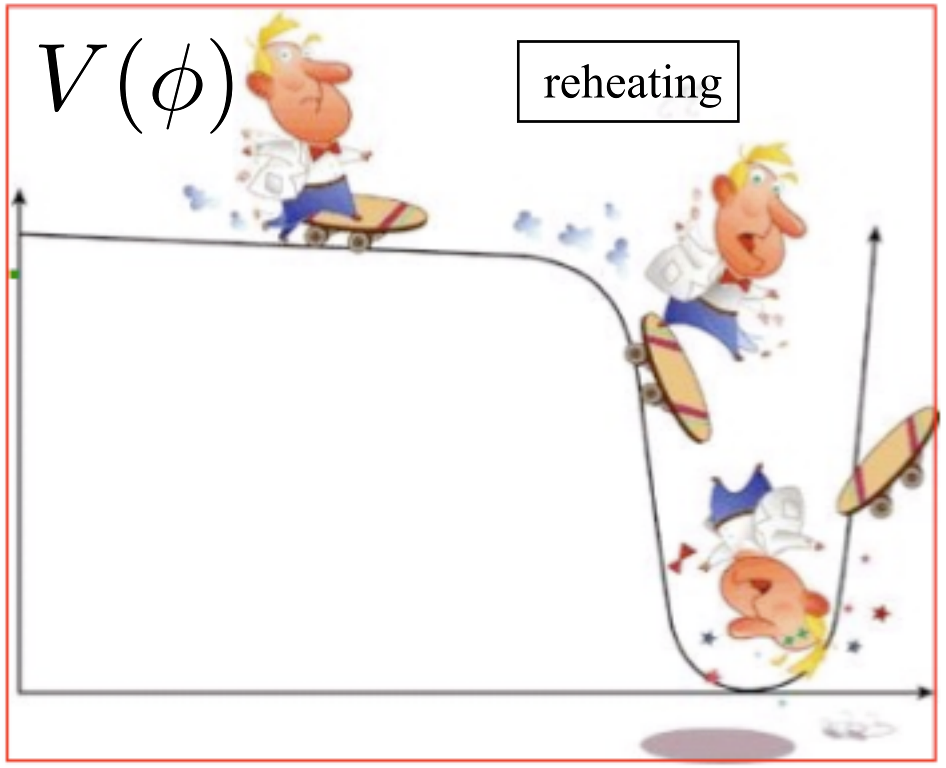
Non-Gaussianity from Inflation

f_{NL} ~ 0.05 canonical inflation (single field, couple of derivatives)
(Maldacena 2003, Acquaviva etal 2003)

f_{NL} ~ 0.1--100 higher order derivatives
- DBI inflation (Alishahiha, Silverstein and Tong 2004)
- UV cutoff (Craminelli and Cosmol, 2003)

f_{NL} >10 curvaton models (Lyth, Ungarelli and Wands, 2003)

f_{NL} ~100 ghost inflation (Arkani-Hamed et al., Cosmol, 2004)



← Inflation →

Lyman Alpha Forest: what can it do?
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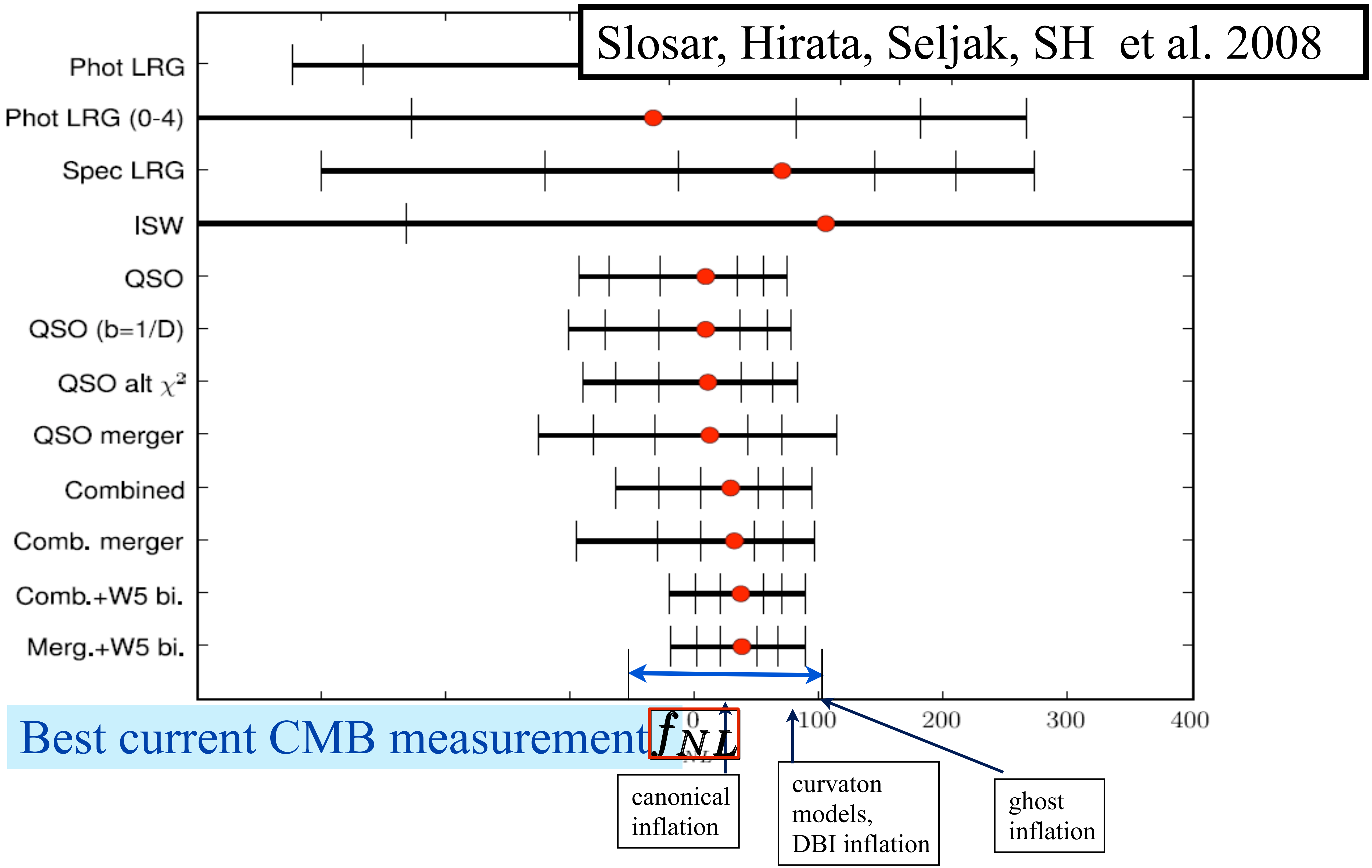

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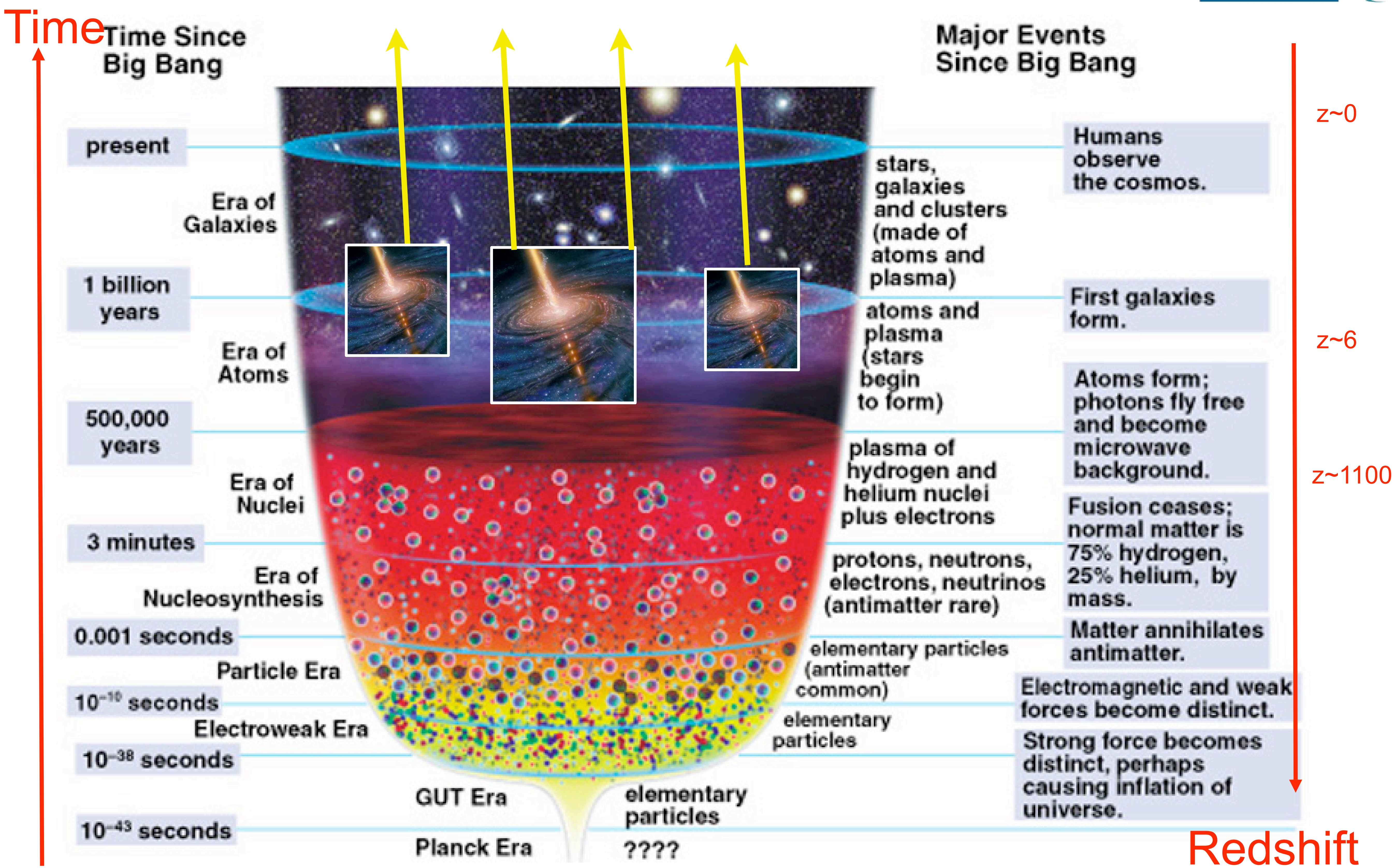
Lyman Alpha Forest: what is it?



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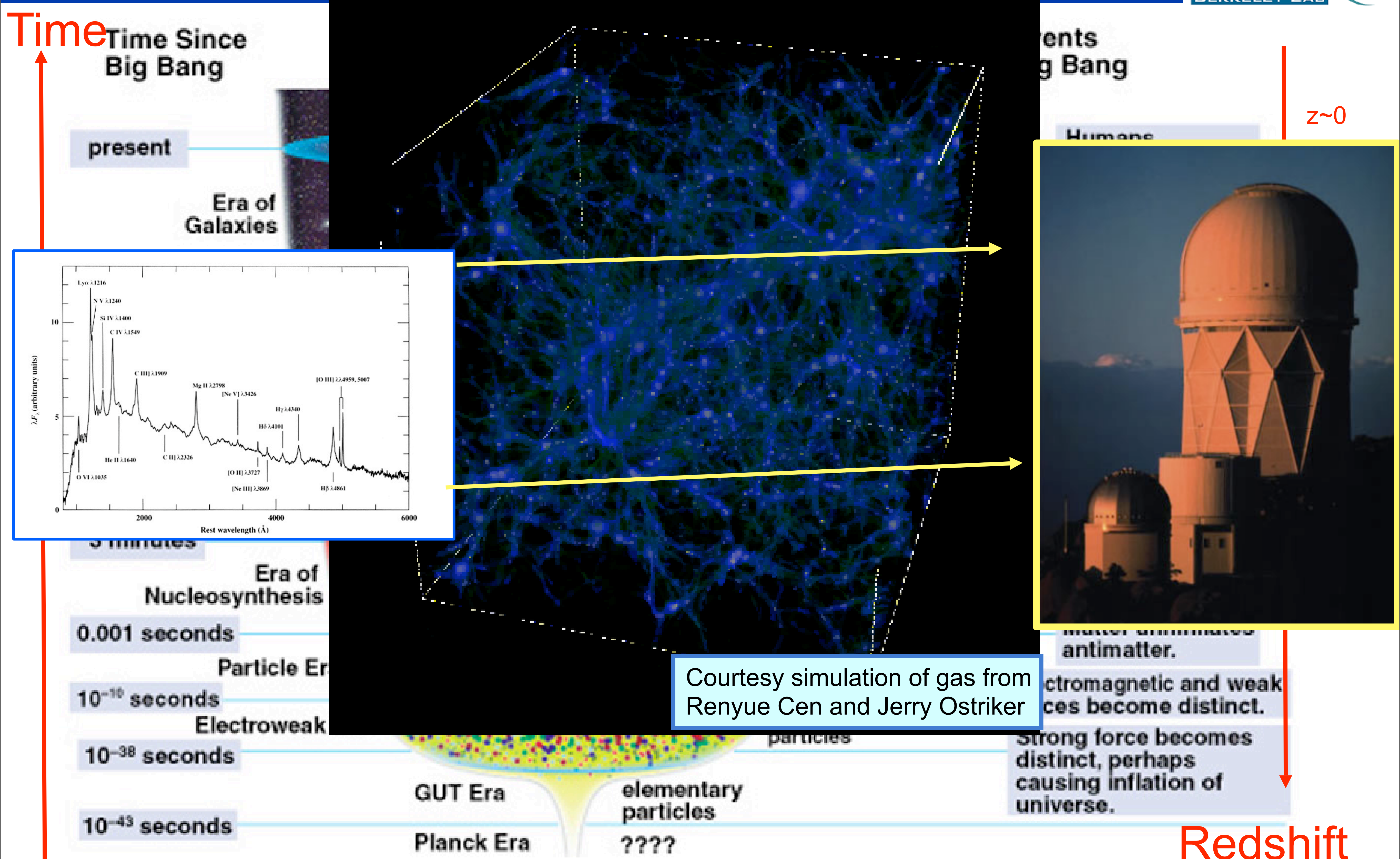
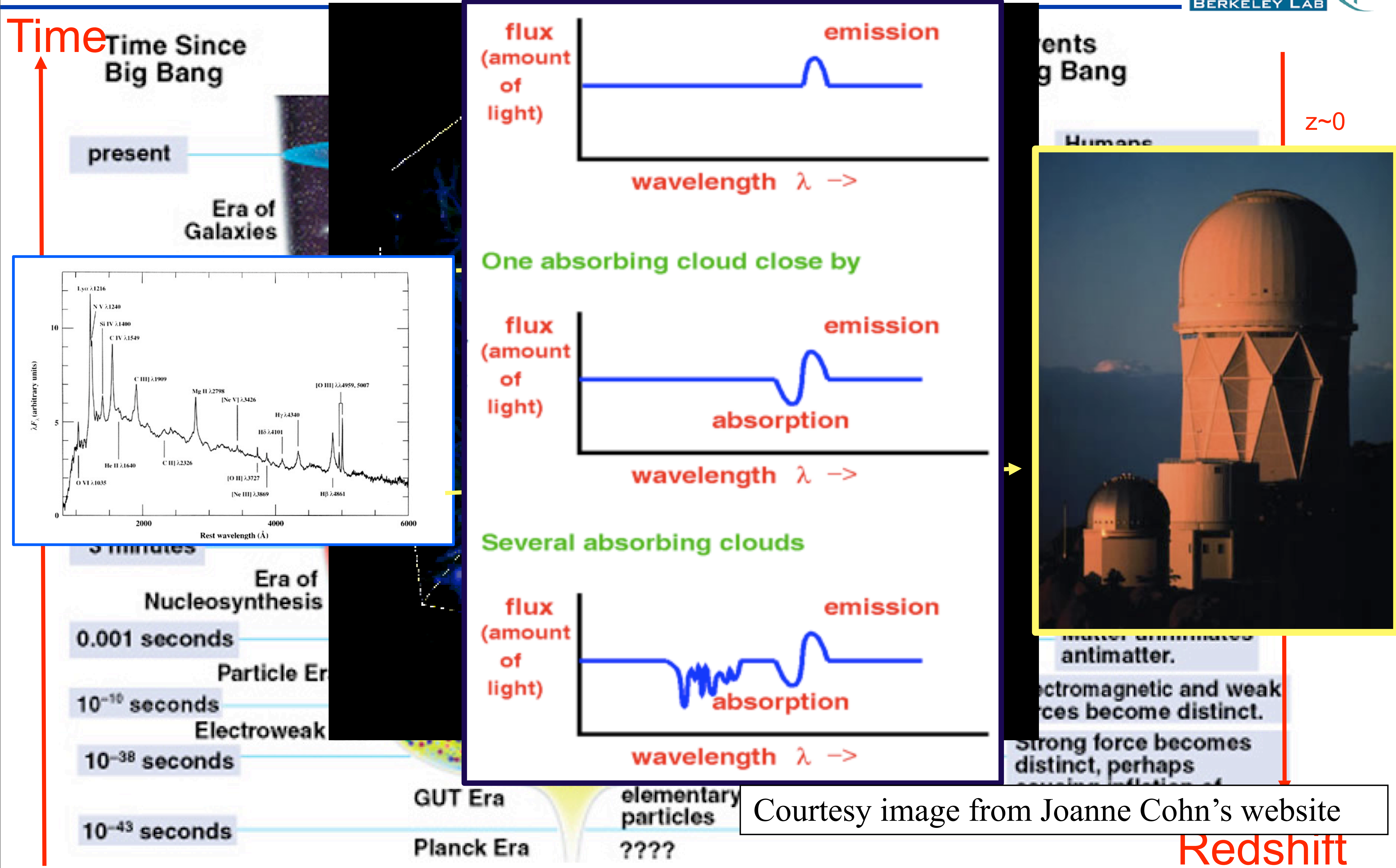


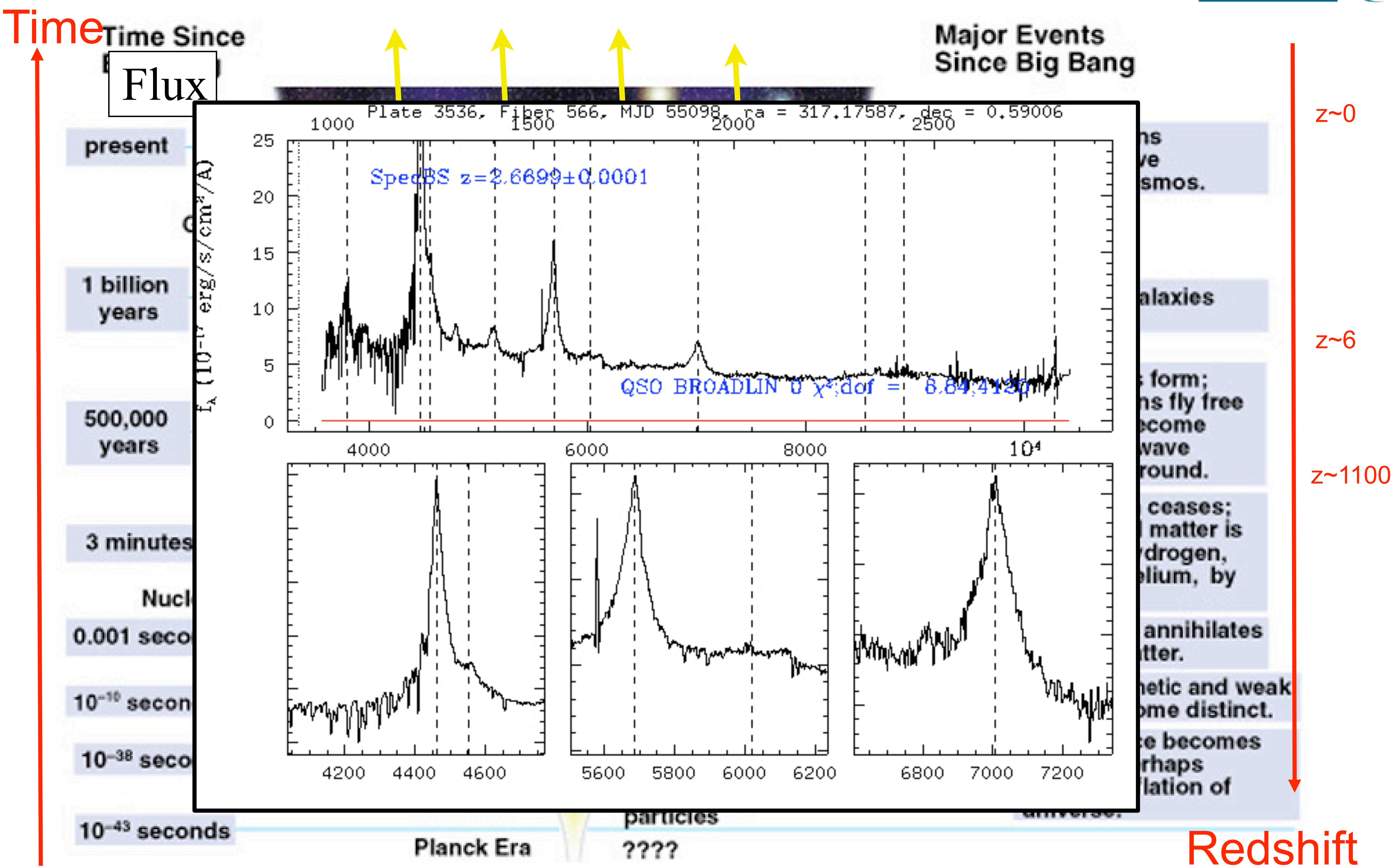
Courtesy simulation of gas from
Renyue Cen and Jerry Ostriker

Lyman Alpha Forest: what is it?



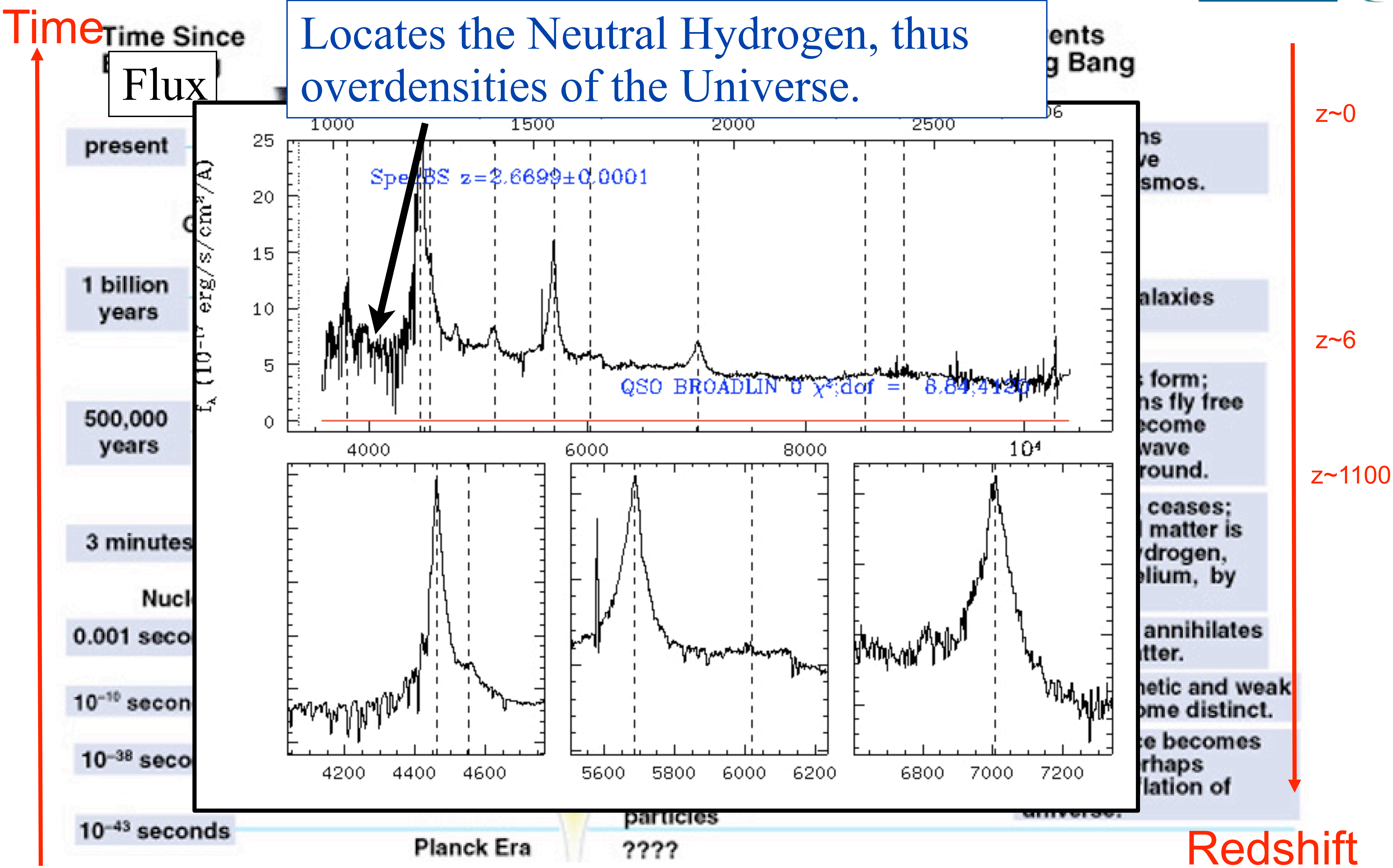
Courtesy image from Joanne Cohn’s website

Lyman Alpha Forest: what is it?



Lyman Alpha Forest: what is it?

Locates the Neutral Hydrogen, thus overdensities of the Universe.



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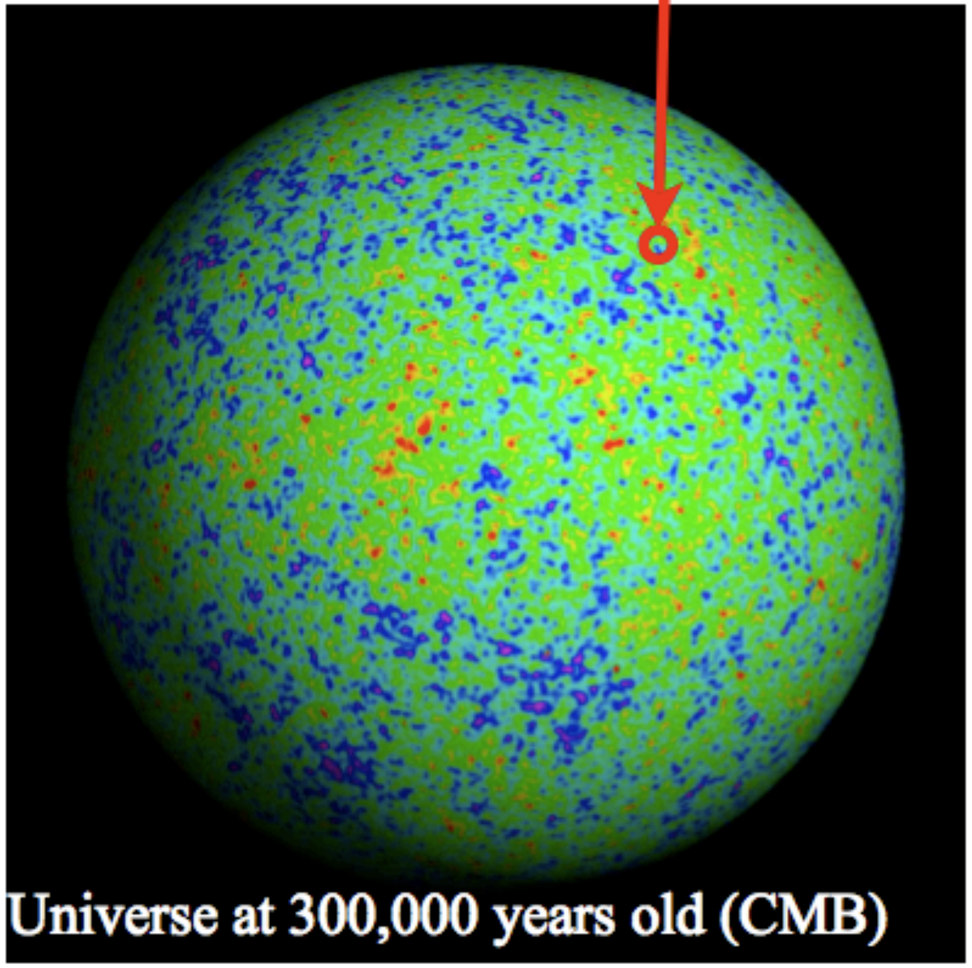
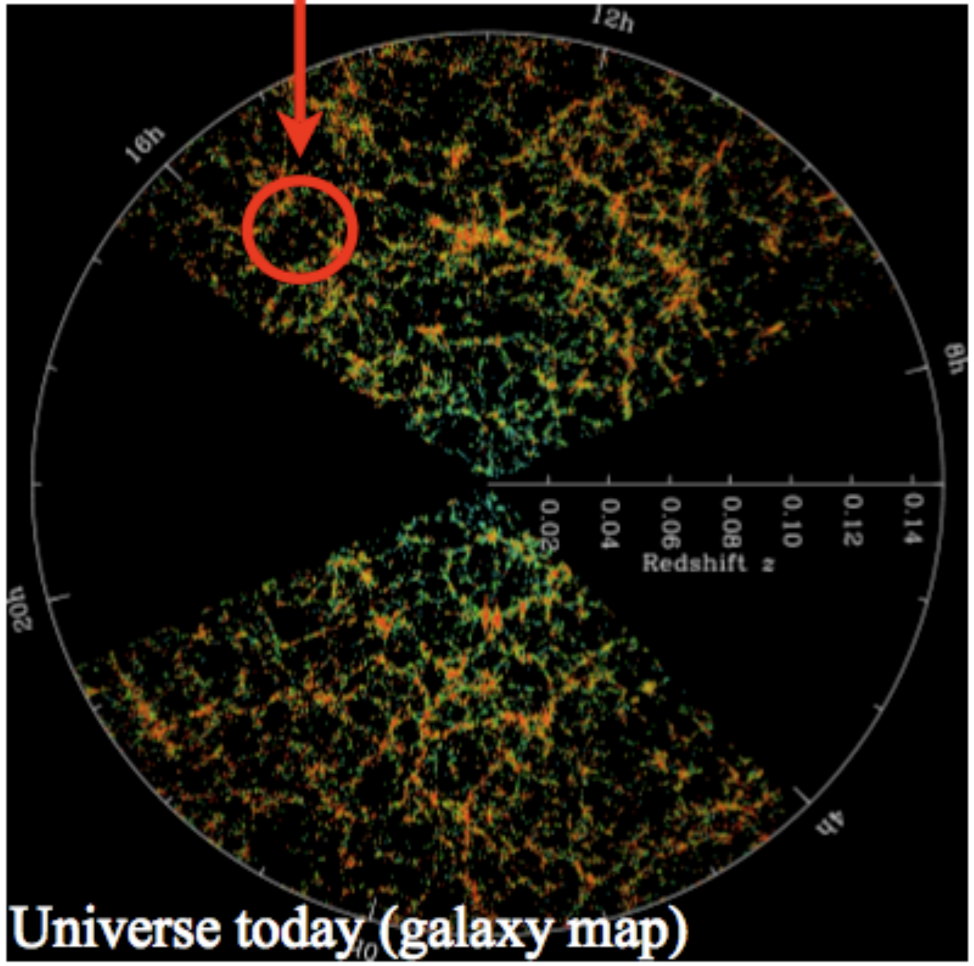
Lyman Alpha Forest: what can it do?

What are baryon acoustic oscillations (BAO)?

These fluctuations of 1 part in 10^5 gravitationally grow into...

...these ~unity fluctuations today





This sound wave can be used as a "standard ruler"

Dark energy changes this apparent ruler size

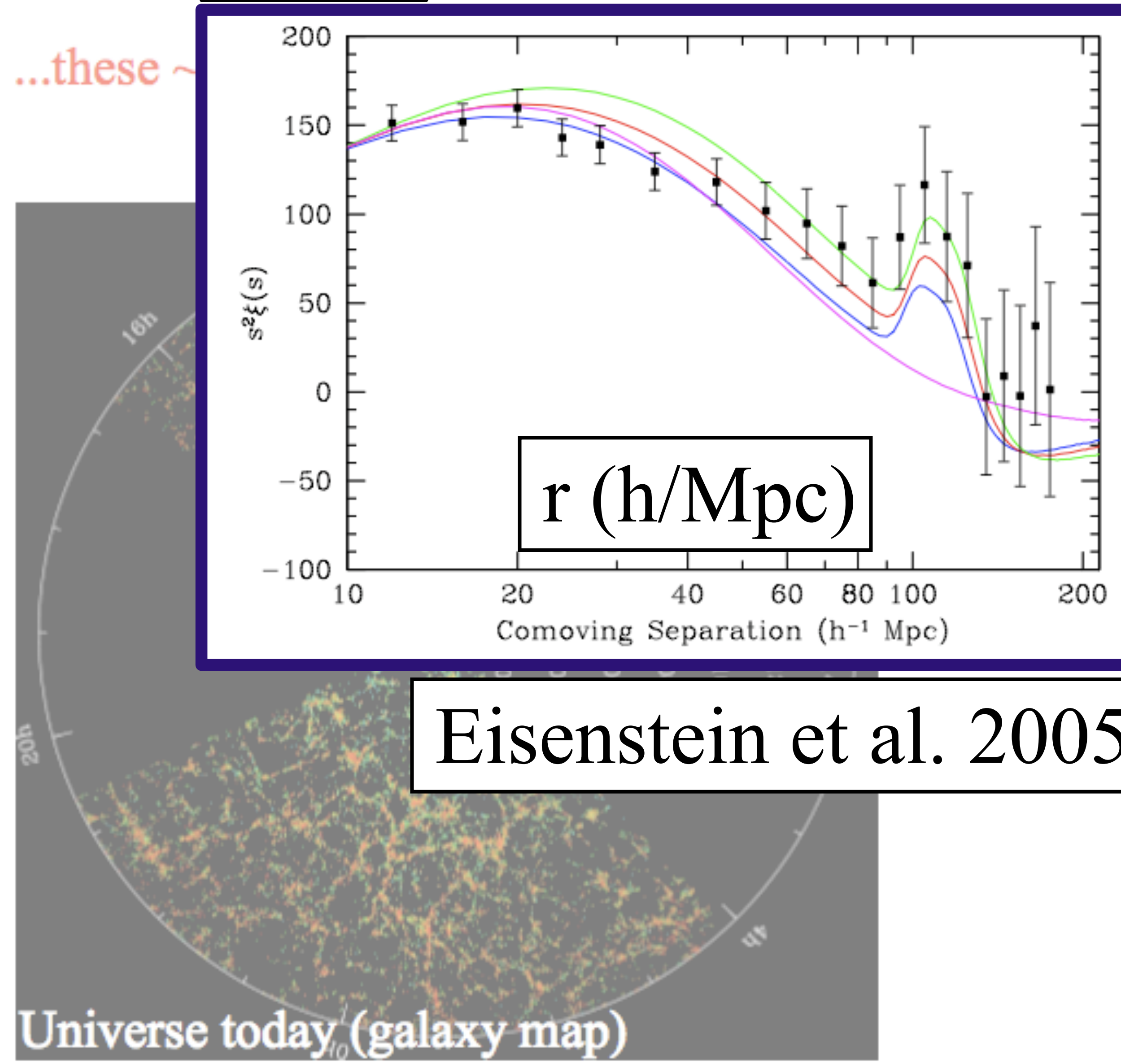
Courtesy slide from David Schlegel

Lyman Alpha Forest: what can it do?

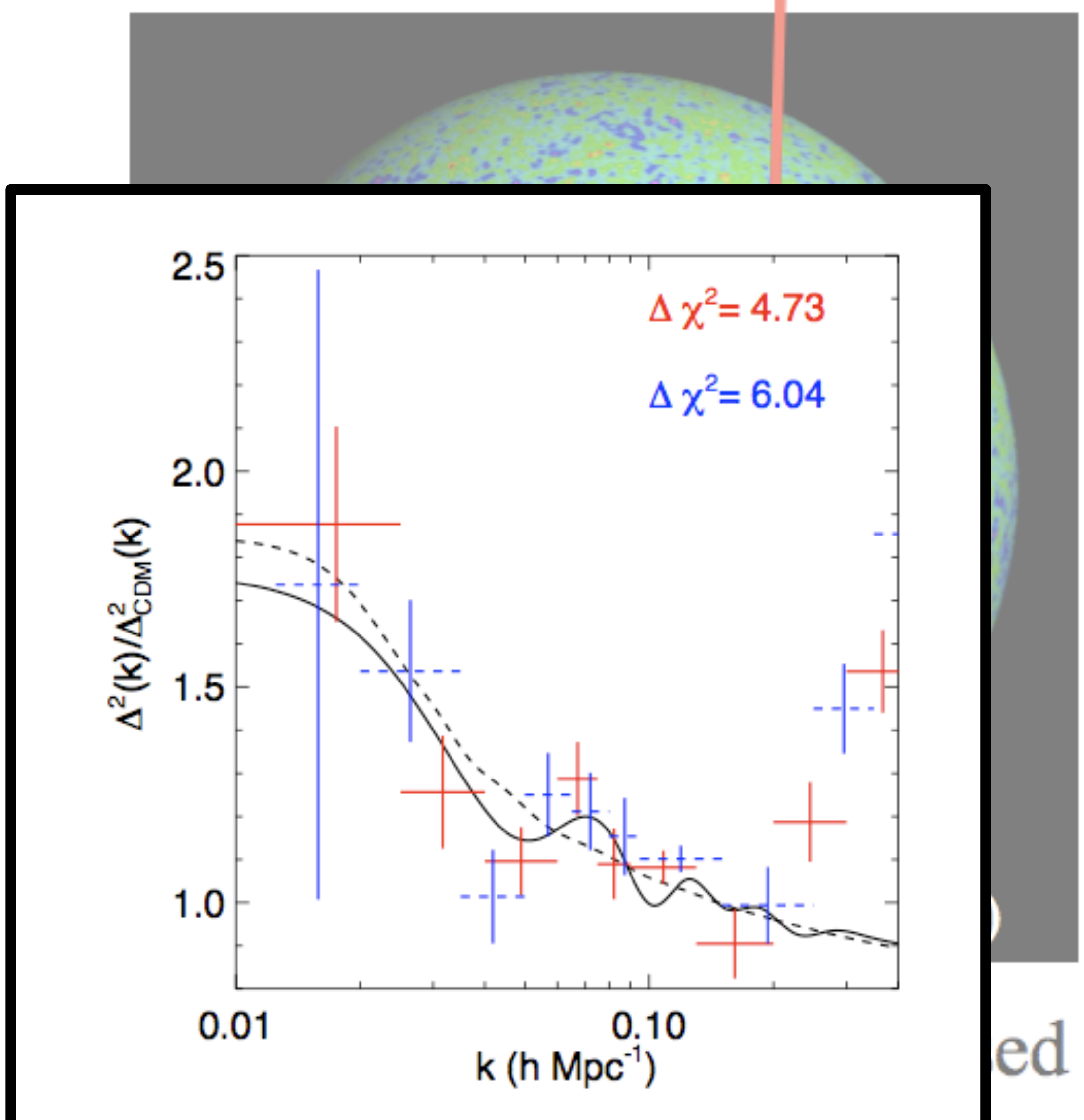
What are baryon acoustic oscillations (BAO)? $r^2\xi(r)$

These fluctuations of 1 part in 10^5 gravitationally grow into…

…these ~



Eisenstein et al. 2005



Padmanabhan et al. 2006

…ed as a "standard ruler"

…apparent ruler size

Courtesy slide from David Schlegel

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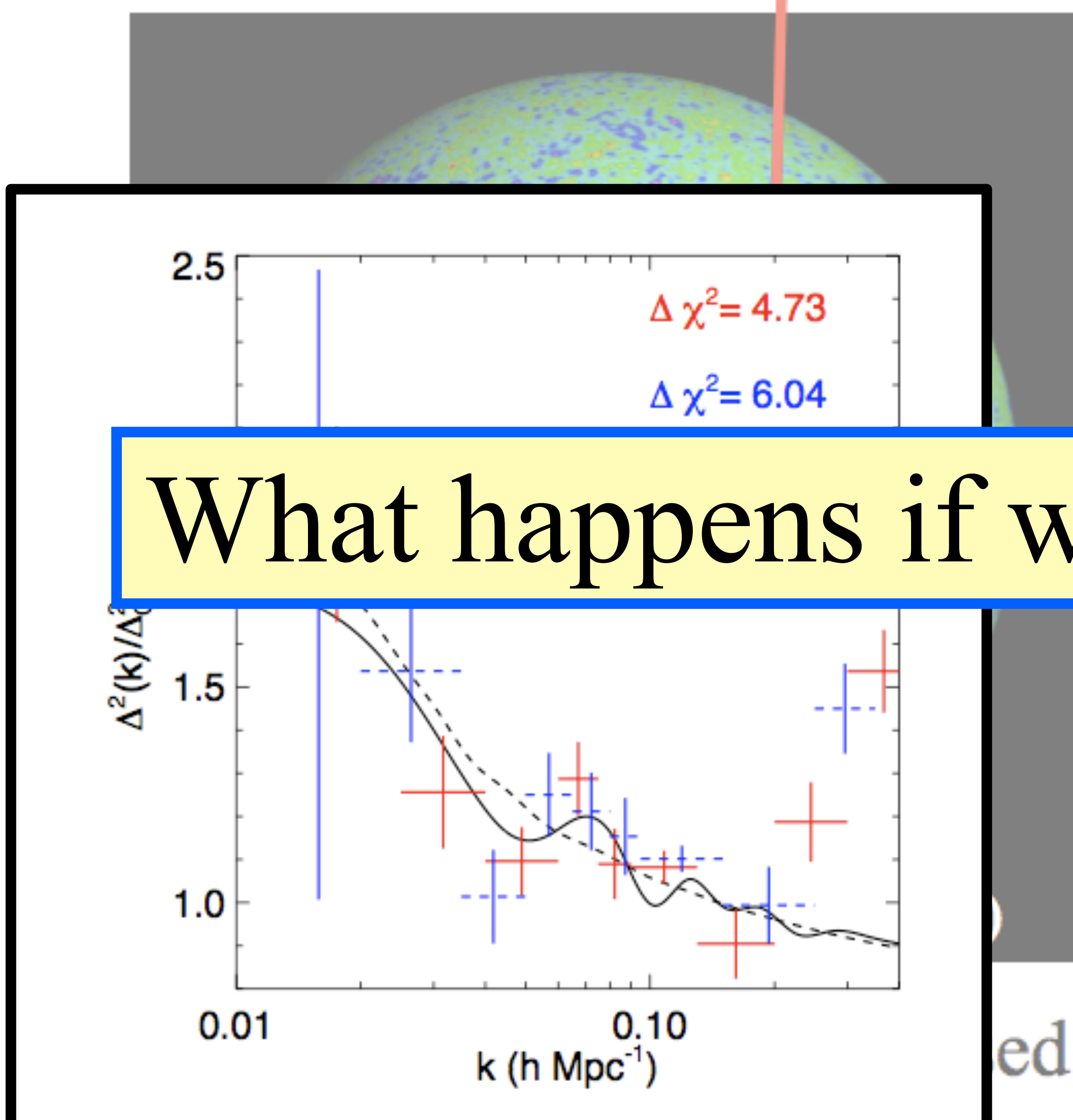

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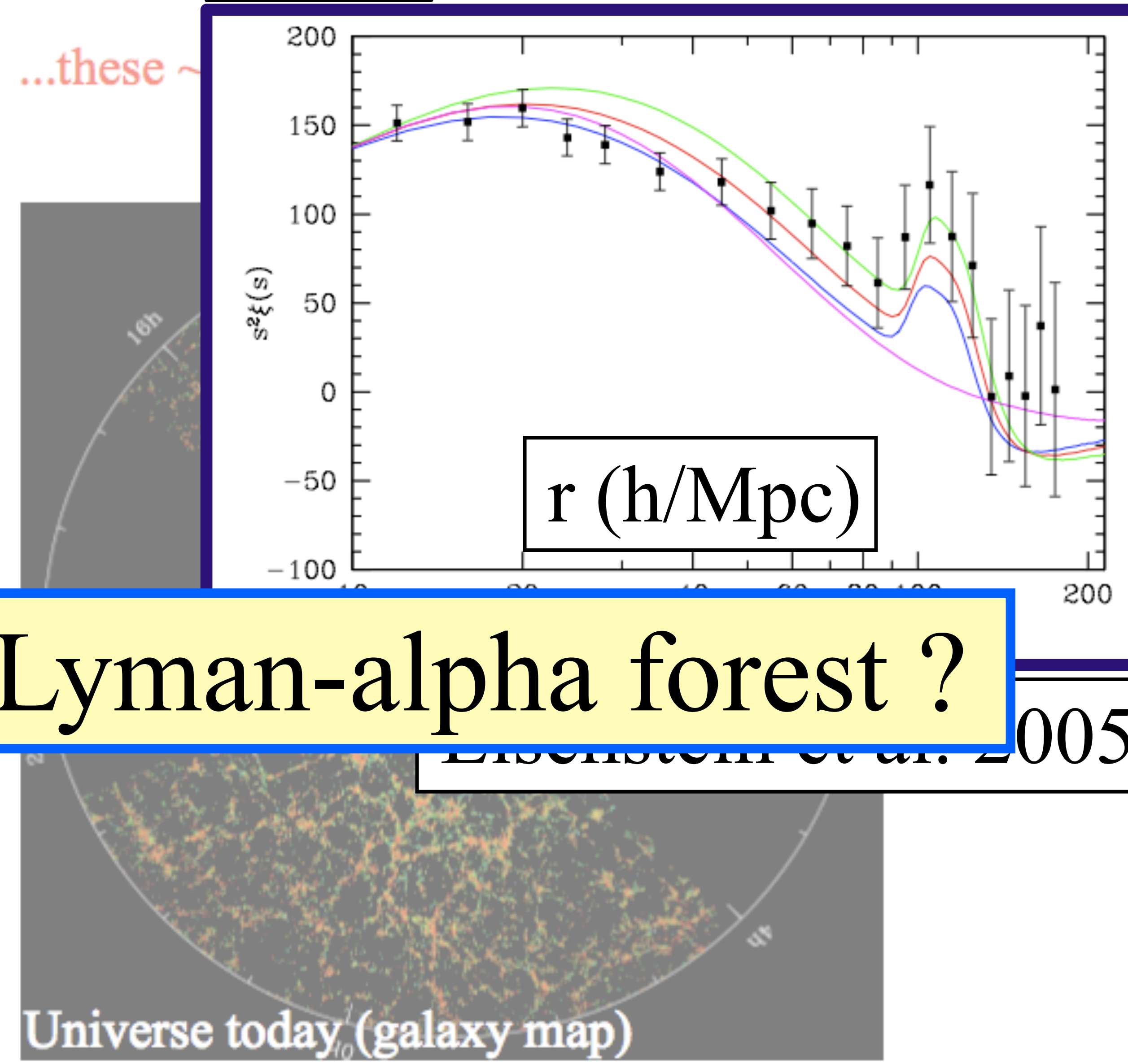


Eisenstein et al. 2005

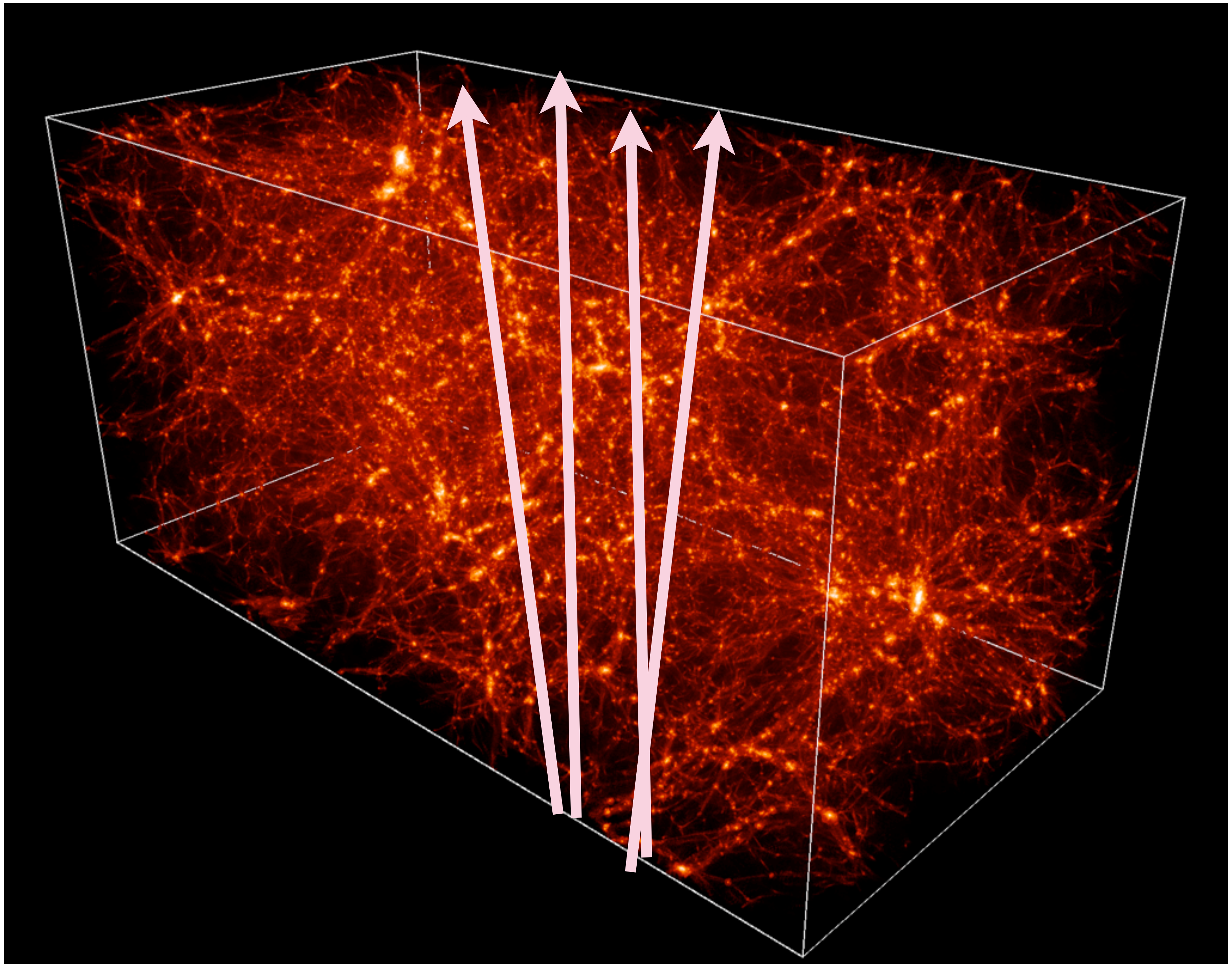
What happens if we use Lyman-alpha forest ?

...ed as a "standard ruler"

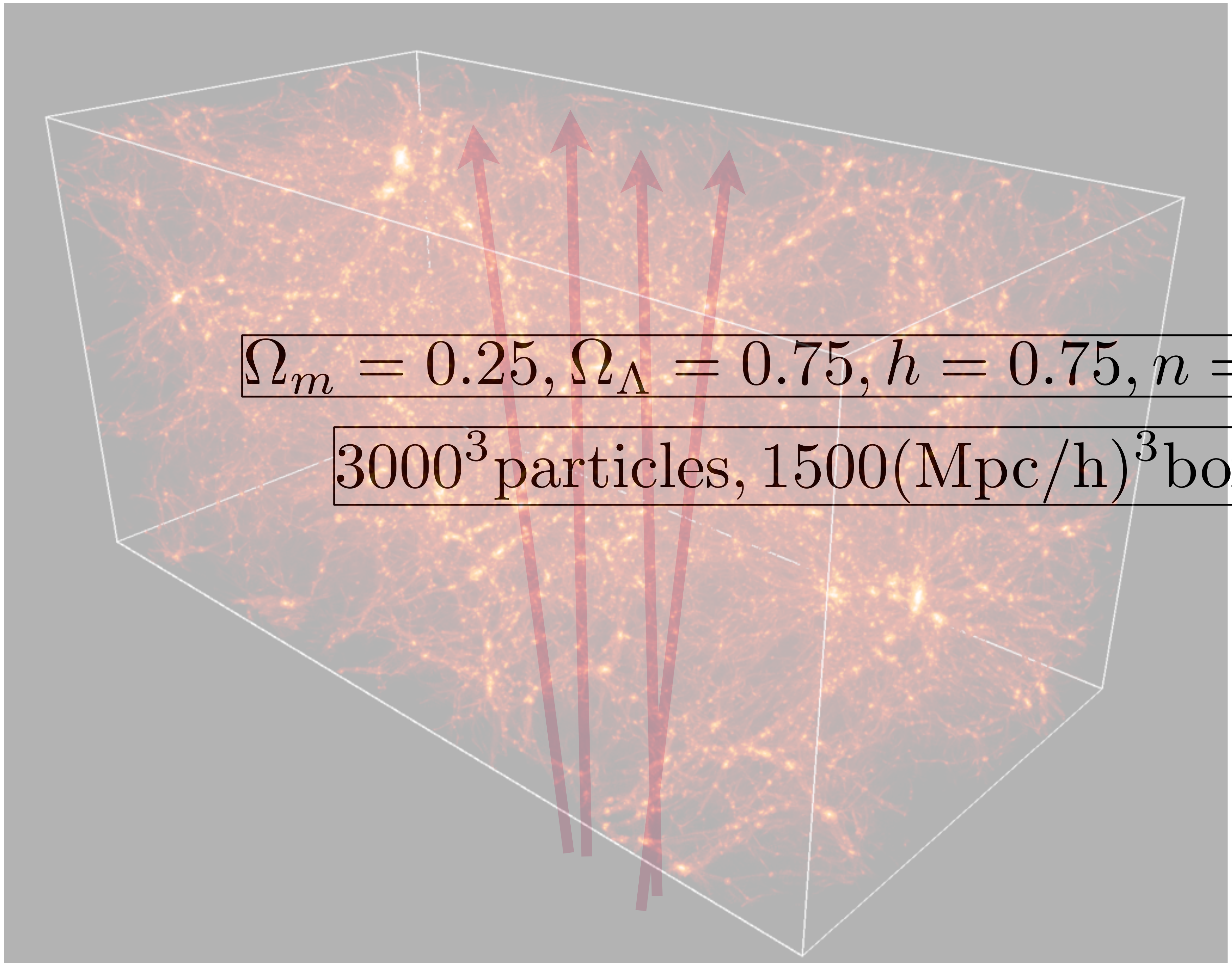
...apparent ruler size

Courtesy slide from David Schlegel

Lyman Alpha Forest: what can it do?



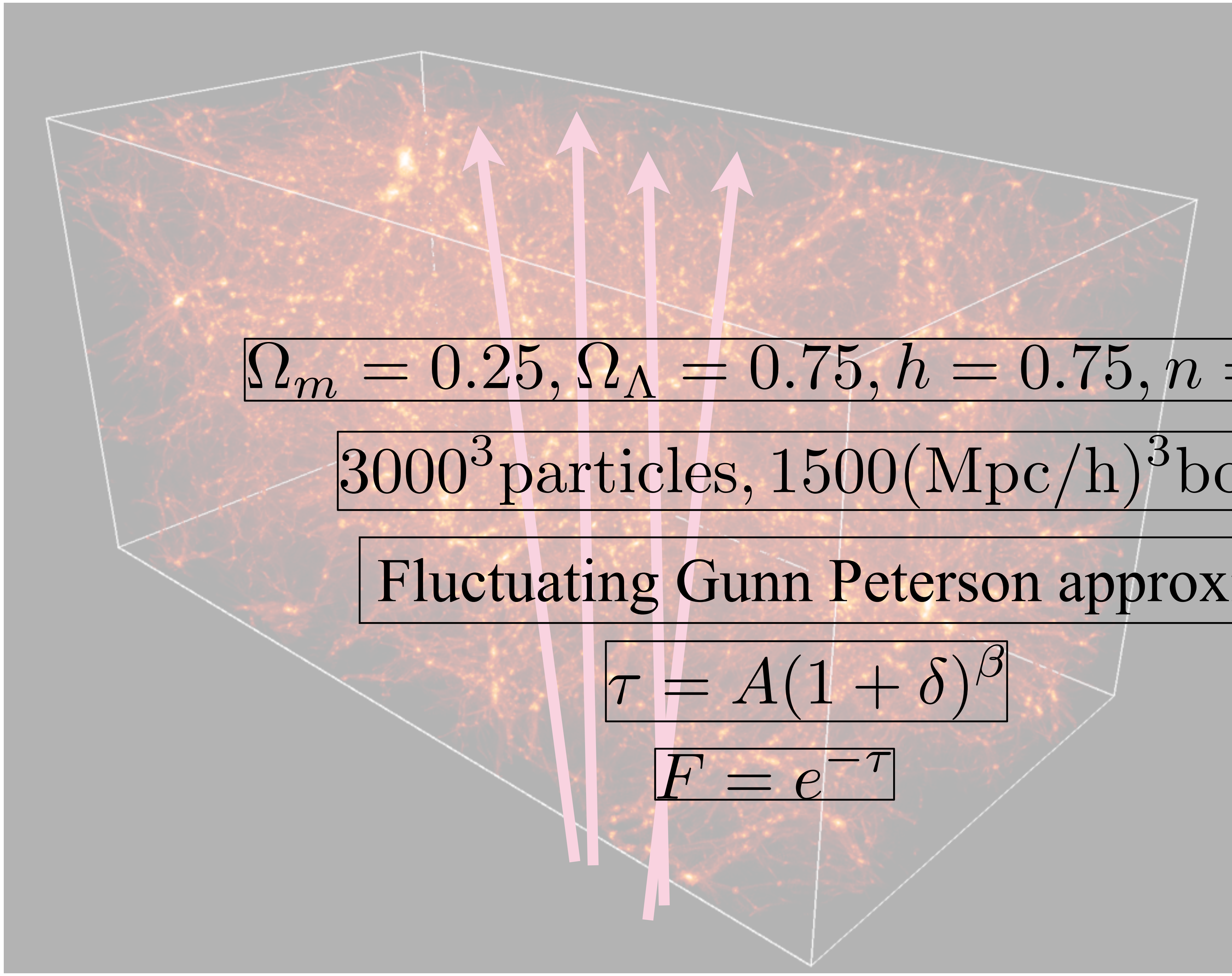
Lyman Alpha Forest: what can it do?



$$\boxed{\Omega_m = 0.25, \Omega_\Lambda = 0.75, h = 0.75, n = 0.97, \sigma_8 = 0.8}$$

$$\boxed{3000^3 \text{particles}, 1500 (\text{Mpc/h})^3 \text{box}, 3000^3 \text{grid}}$$

Lyman Alpha Forest: what can it do?



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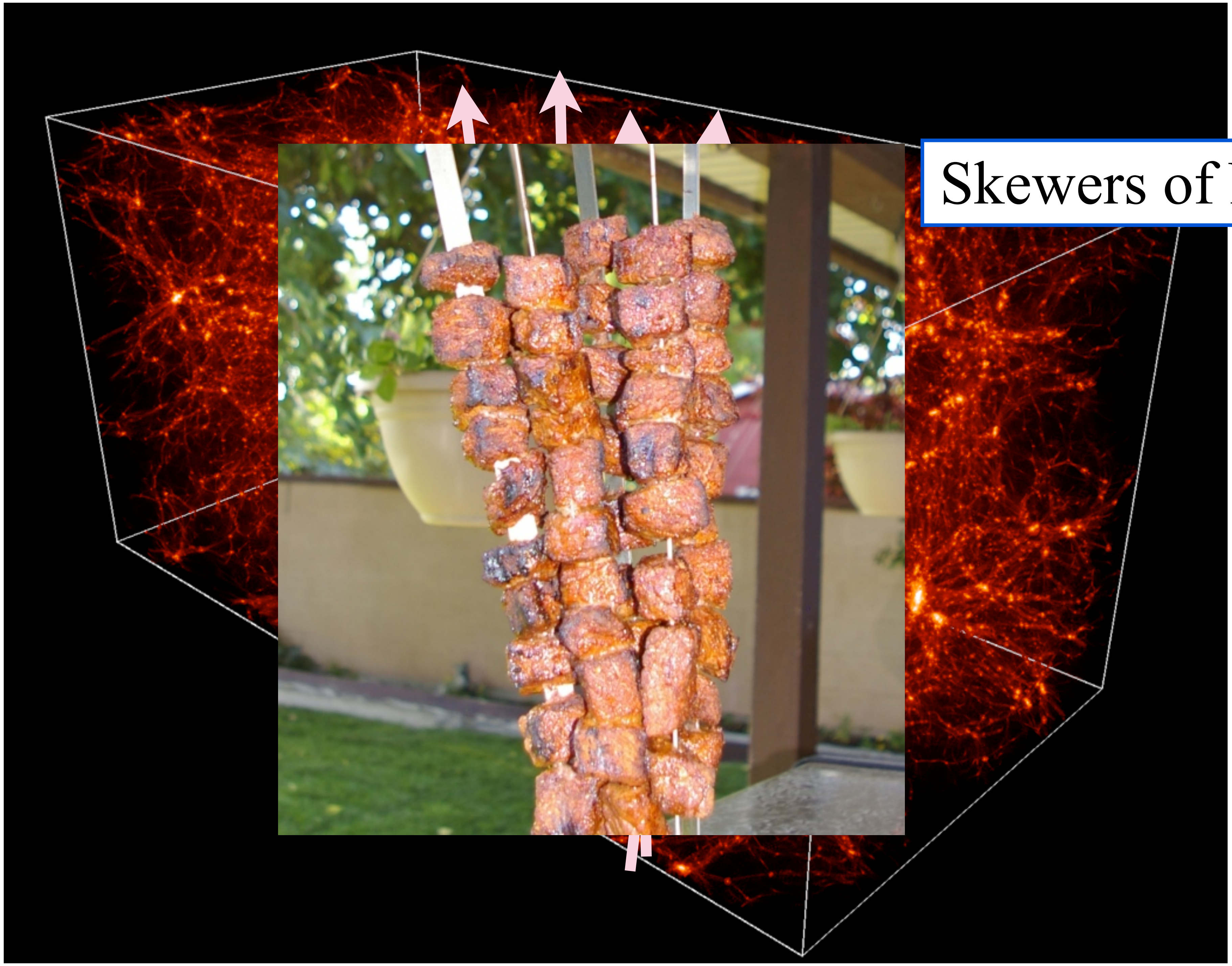
Fluctuating Gunn Peterson approximation

$\boxed{\tau = A(1+\delta)^\beta}$

$\boxed{F = e^{-\tau}}$

Lyman Alpha Forest: what can it do?

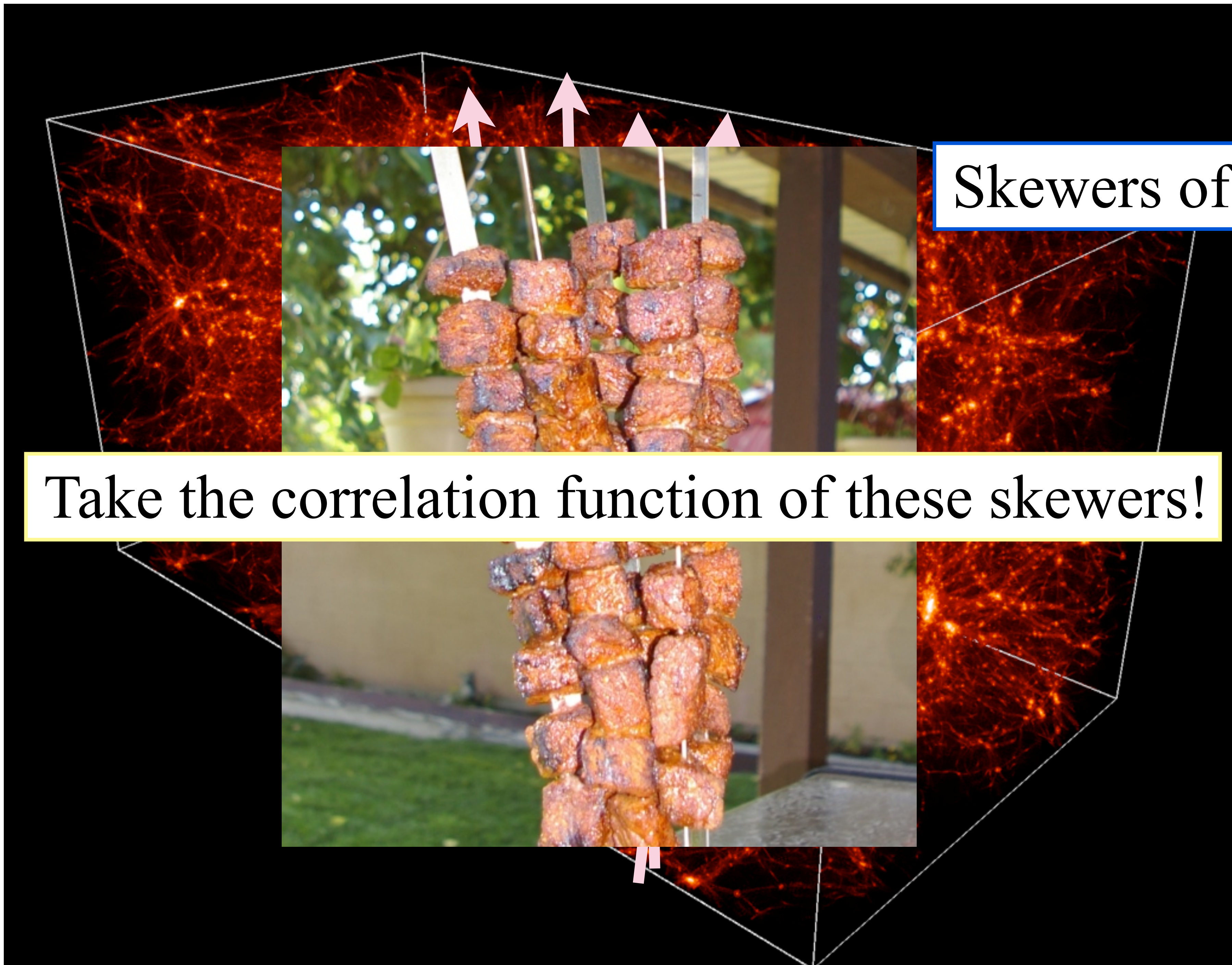
- **Dark Energy via Baryon Acoustic Oscillations**



Skewers of Neutral Hydrogen

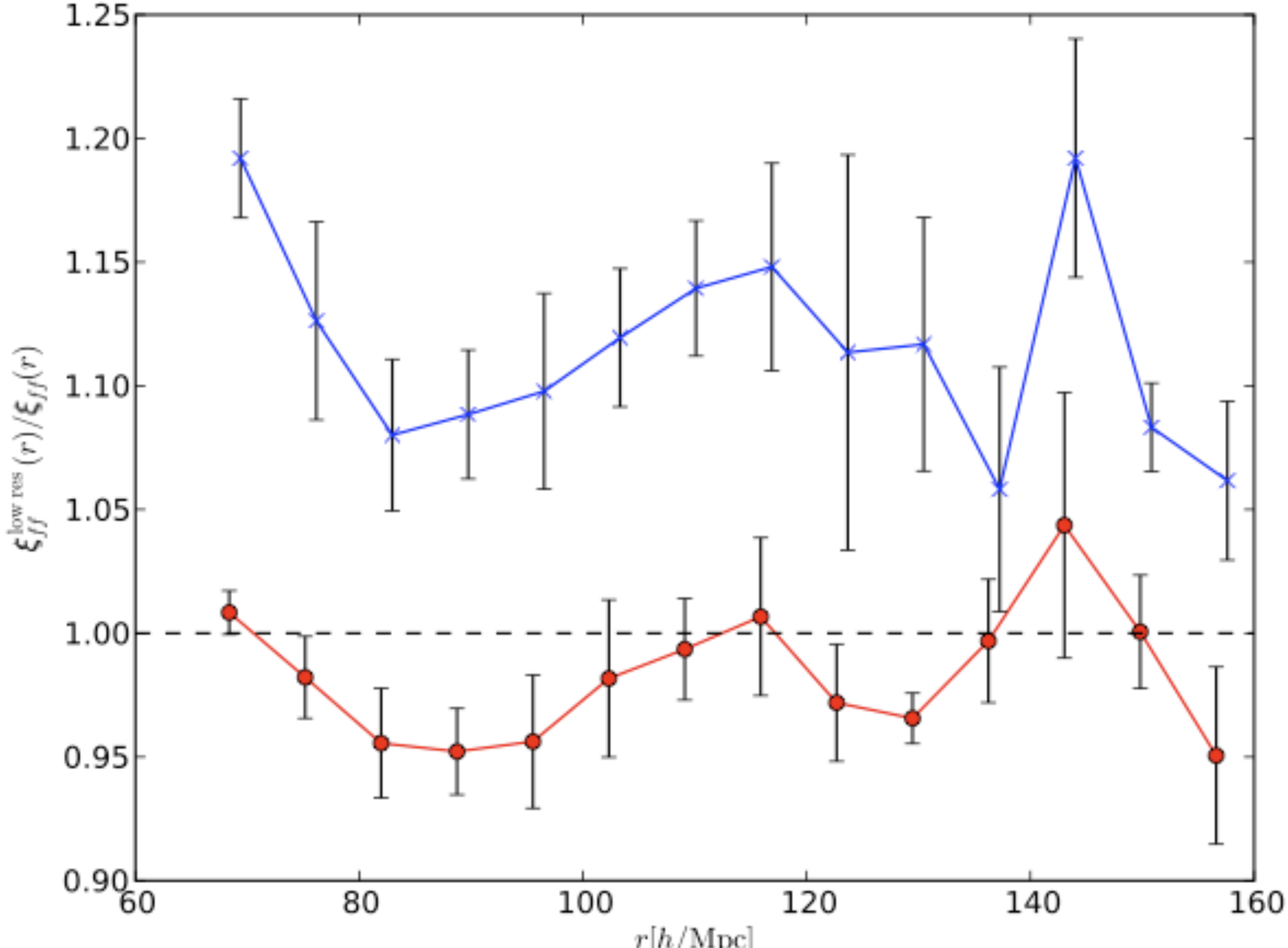
Lyman Alpha Forest: what can it do?

- **Dark Energy via Baryon Acoustic Oscillations**



How about the resolution effect?

$$\xi_{ff}^{\rm lowres}(r)/\xi_{ff}(r)$$



resolution 4X worse

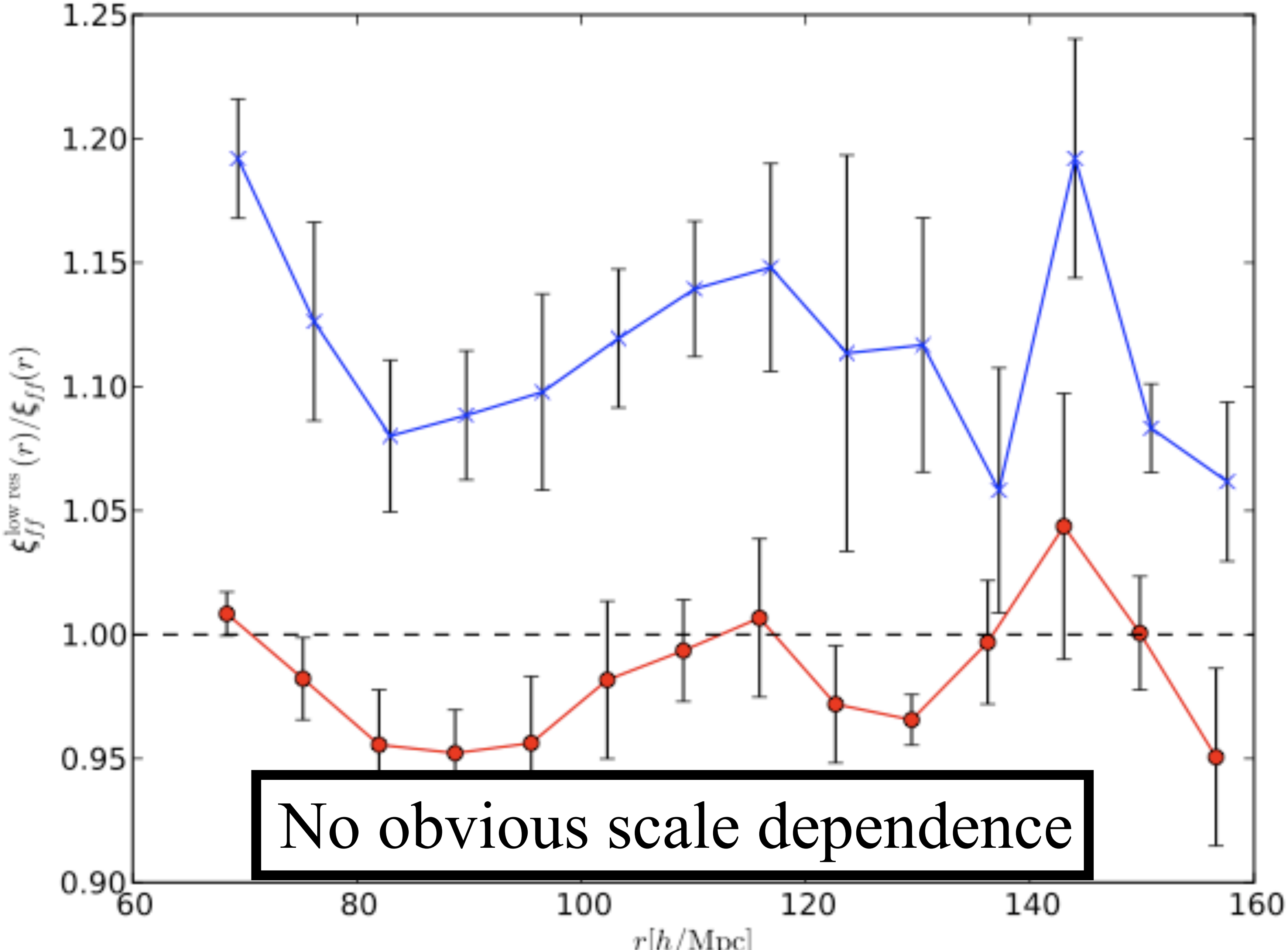
resolution 2X worse

$$r[h/Mpc]$$

Slosar, SH, White & Louis (2009)

How about the resolution effect?

$\xi_{ff}^{\text{lowres}}(r)/\xi_{ff}(r)$



$r[h/Mpc]$

resolution 4X worse

resolution 2X worse

Slosar, SH, White & Louis (2009)

Lyman Alpha Forest: what can it do?

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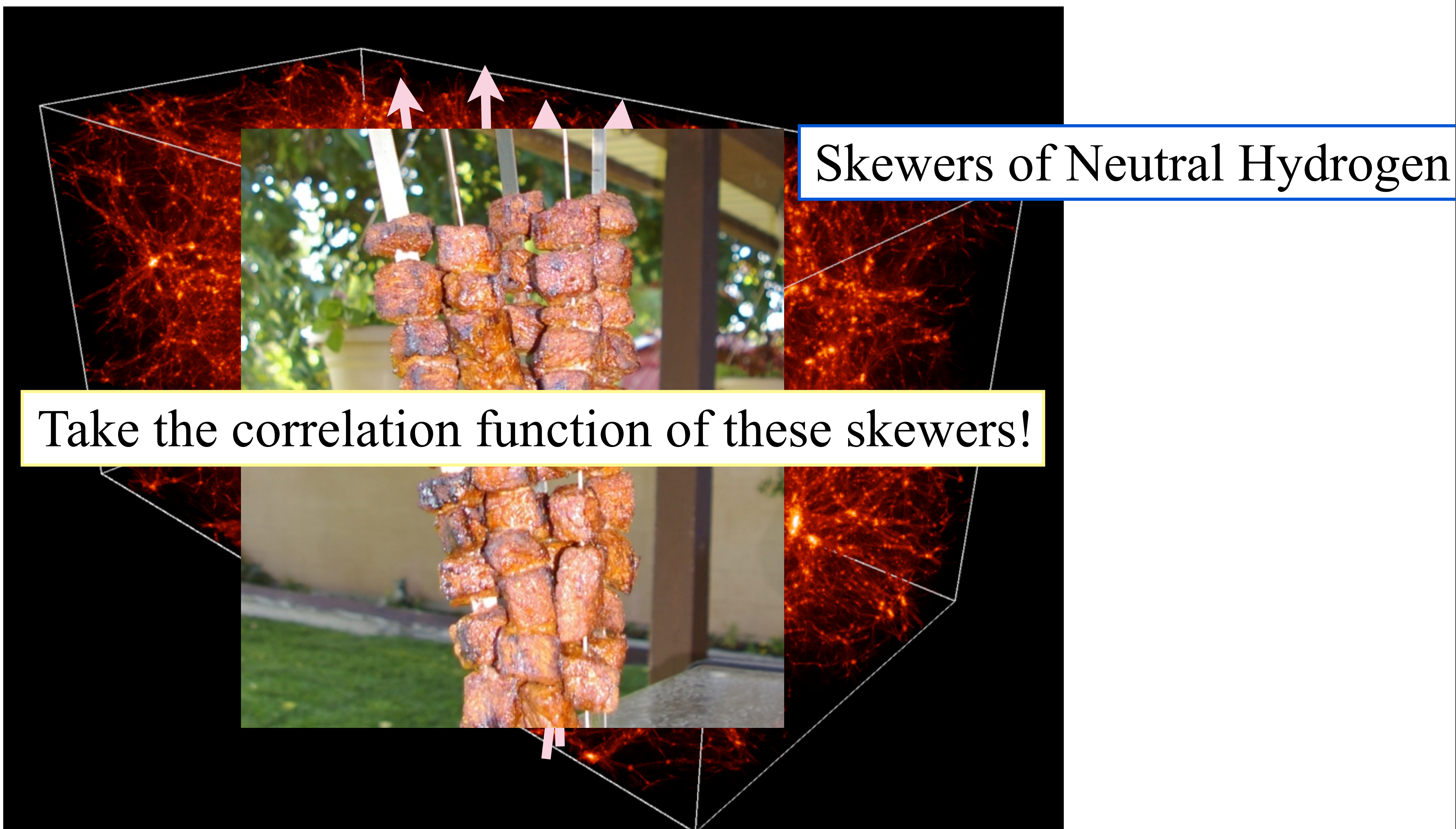

Lyman Alpha Forest: what can it do?

- **Dark Energy via Baryon Acoustic Oscillations**

—the correlation function:

$$\xi_f(r) =< \delta_f(\hat{x})\delta_f(\hat{x}+\hat{r}) >$$

Lyman Alpha Forest: what can it do?

- **Dark Energy via Baryon Acoustic Oscillations**

—the correlation function:

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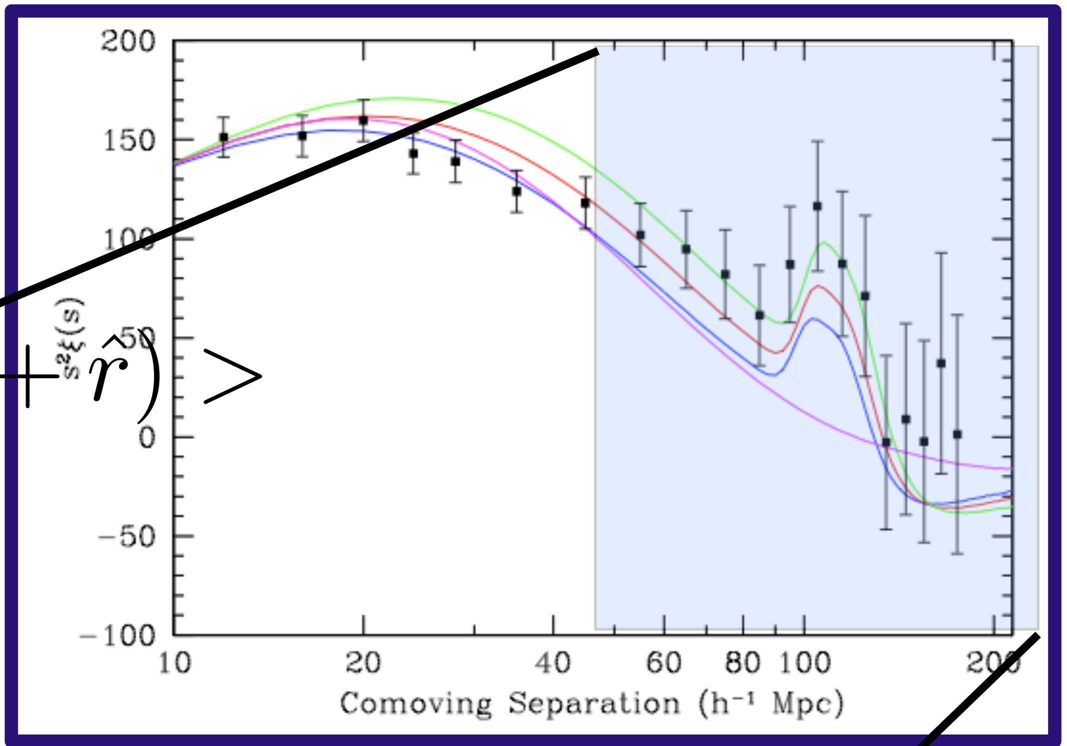
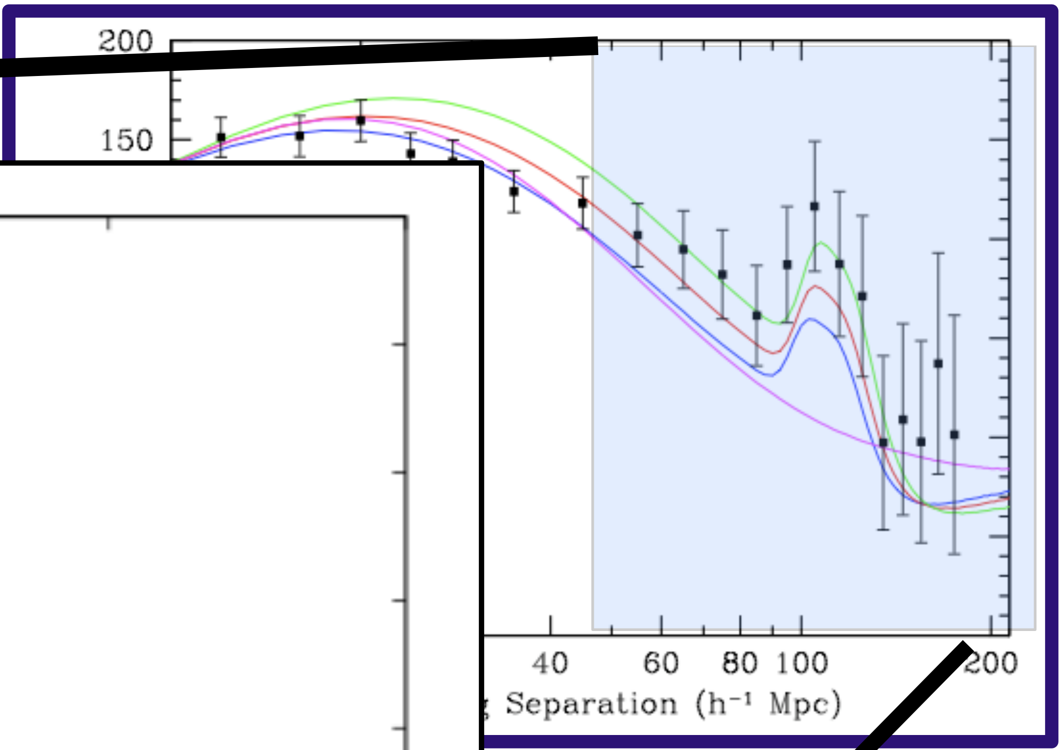


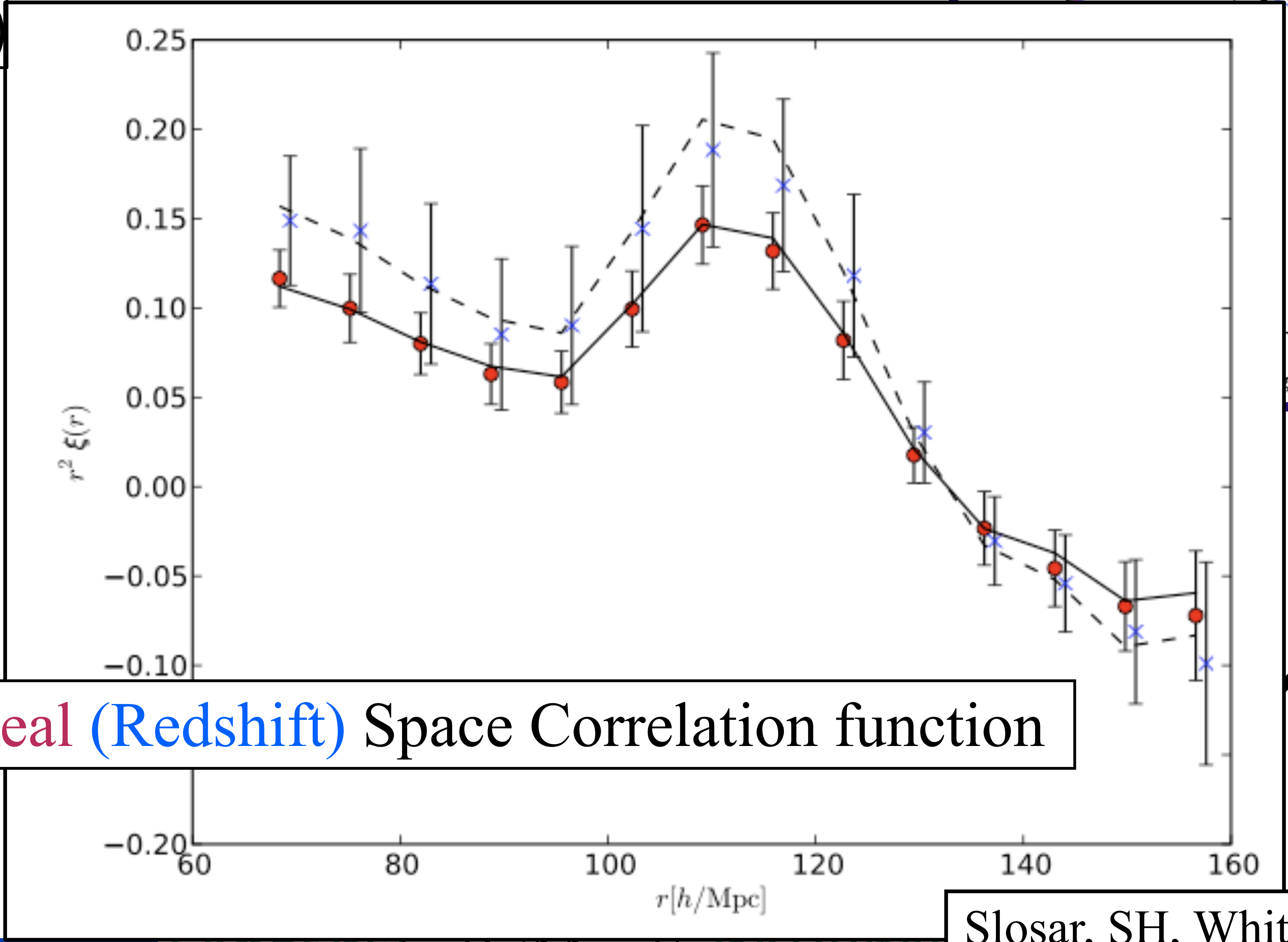
Lyman Alpha Forest: what can it do?

- **Dark Energy via Baryon Acoustic Oscillations**

take the correlation function:

$r^2\xi(r)$



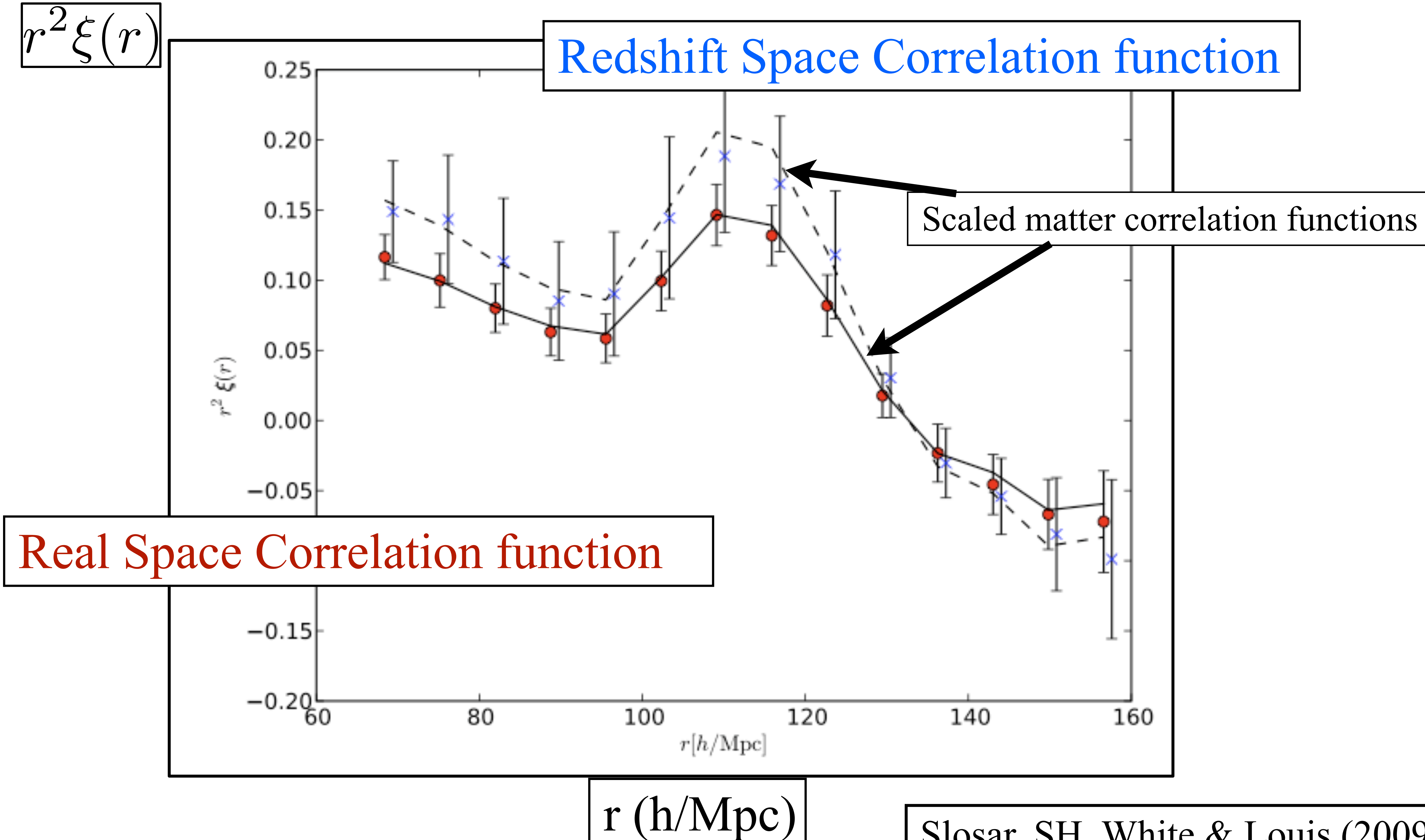


Flux Real (Redshift) Space Correlation function

r (h/Mpc)

Slosar, SH, White & Louis (2009)

Lyman Alpha Forest: what can it do?



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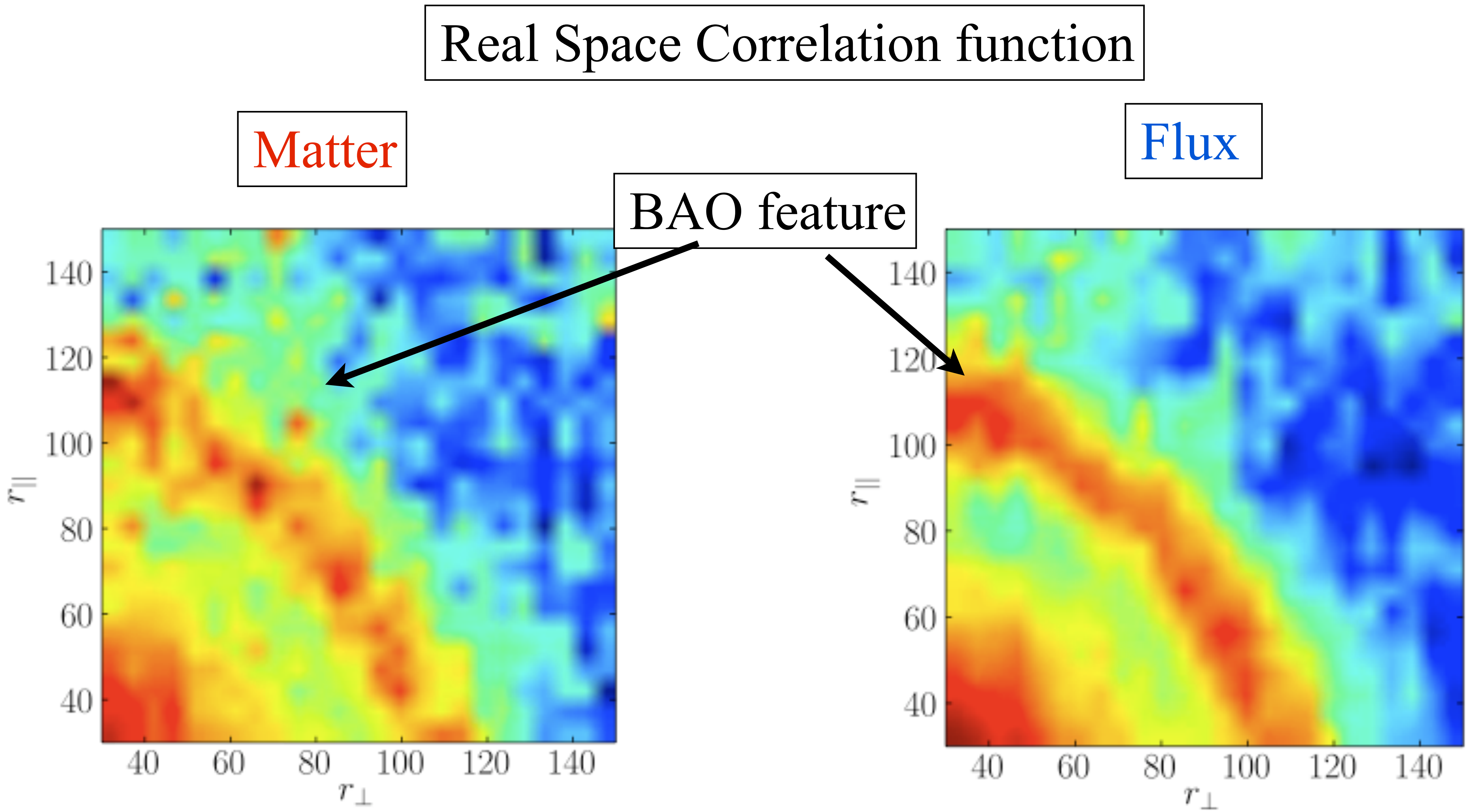


Slosar, SH, White & Louis (2009)

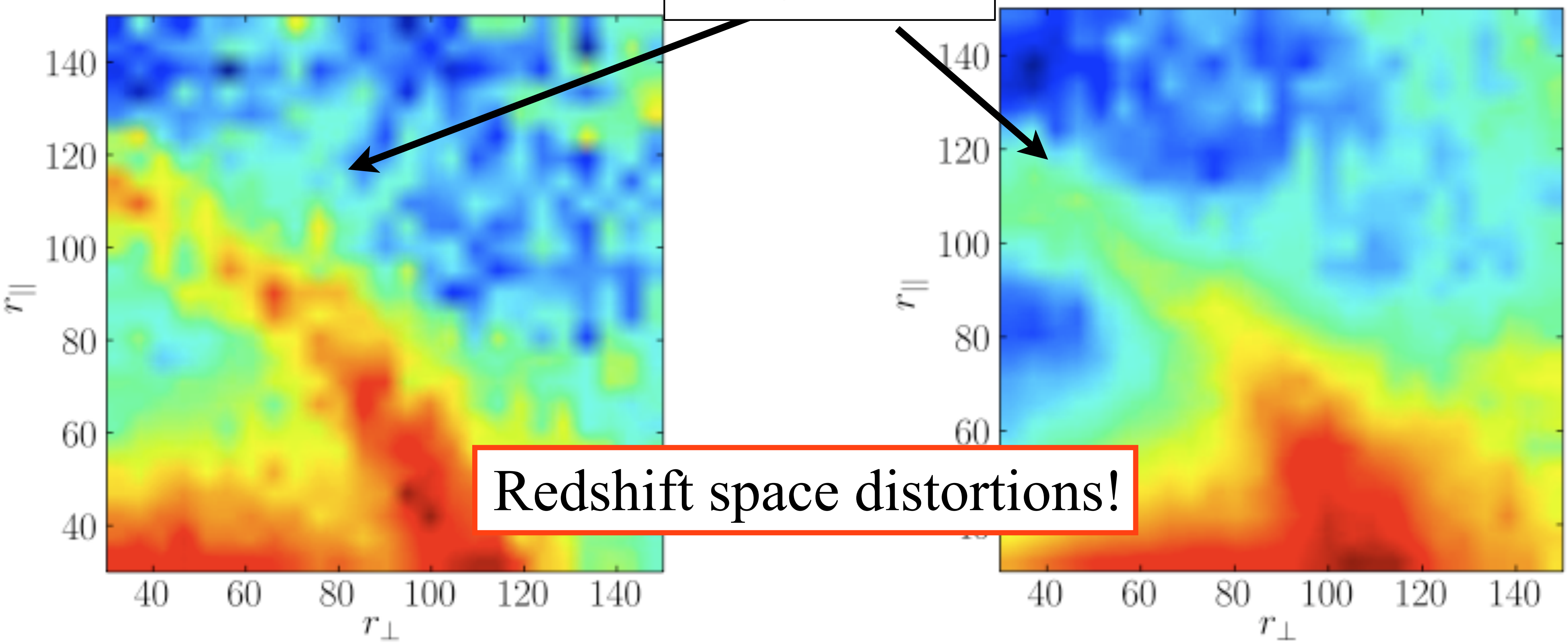
Lyman Alpha Forest: what can it do?

Redshift Space Correlation function

Matter

Flux

BAO feature



Redshift space distortions!

Slosar, SH, White & Louis (2009)

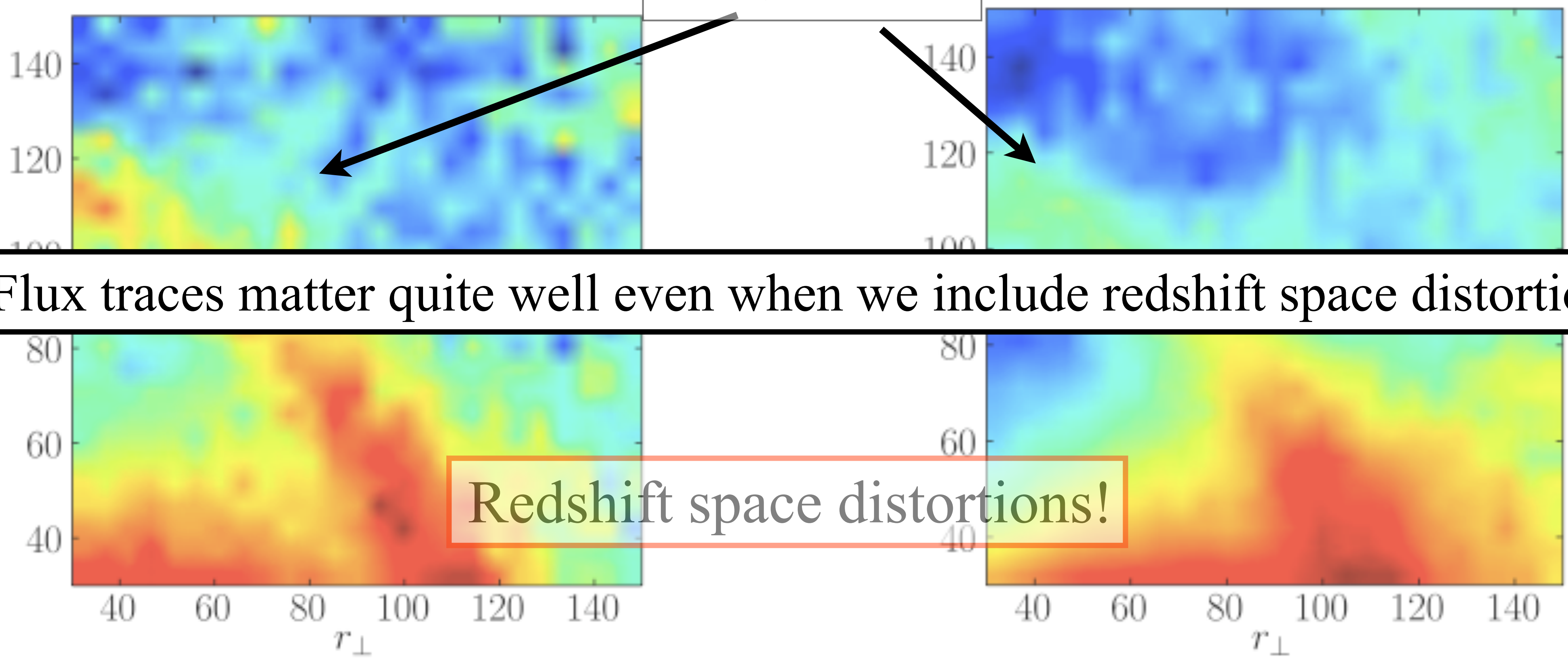
Lyman Alpha Forest: what can it do?

Redshift Space Correlation function

Matter

Flux

BAO feature



Flux traces matter quite well even when we include redshift space distortions!

Slosar, SH, White & Louis (2009)

Lyman Alpha Forest: what can it do?

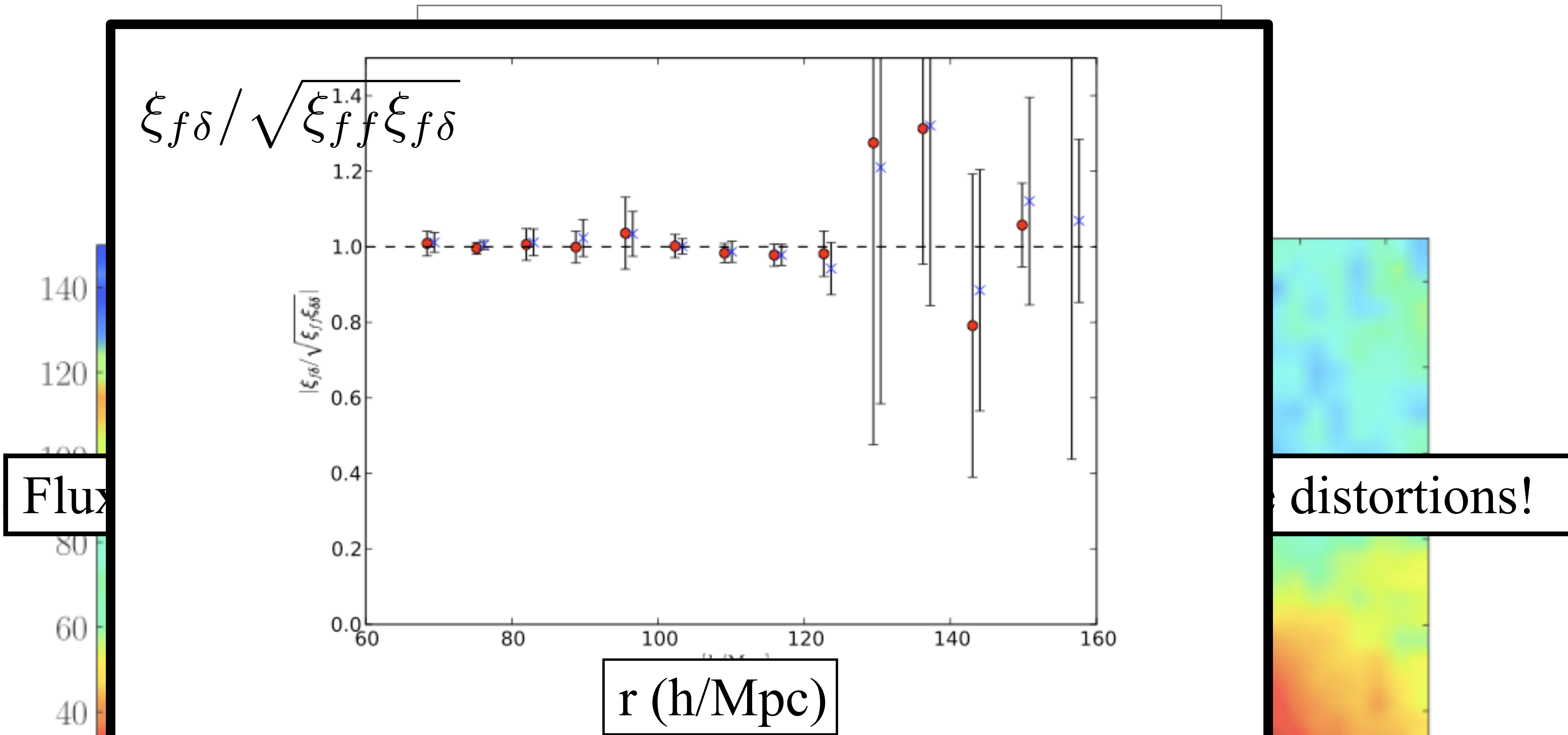


FIG. 7: The cross-correlation coefficient between flux and matter over-density in real (red) and redshift (blue) space.

Slosar, SH, White & Louis (2009)

Lyman Alpha Forest: what can it do?

Redshift Space Correlation function

Matter

Flux

BAO feature

But what how should we deal with this redshift space distortion ?

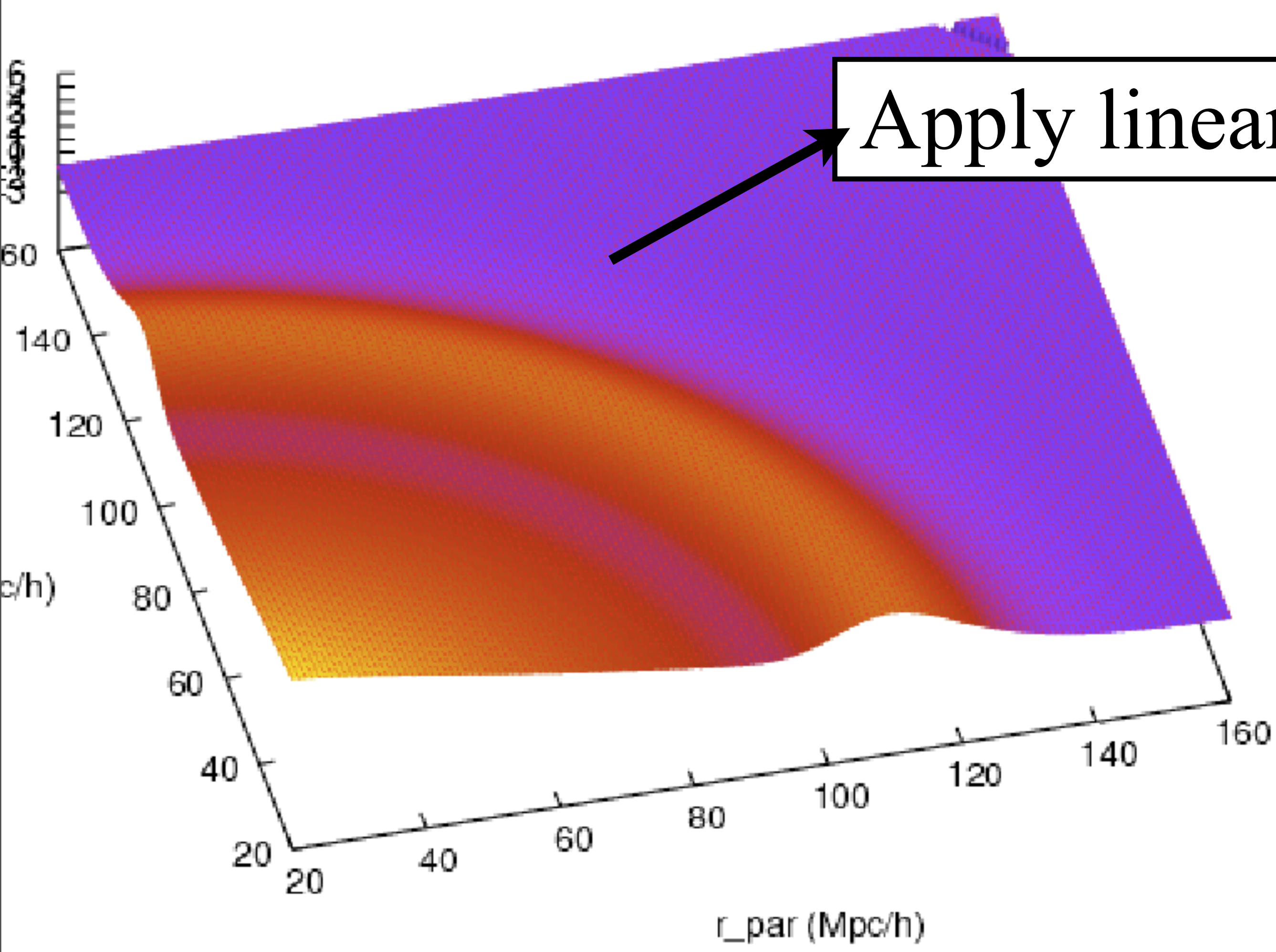
Flux traces matter quite well even when we redshift space distortions!

Redshift space distortions!

Lyman Alpha Forest: what can it do?

No z-space distortion

z-space distortions



Apply linear Kaiser formula

$$\xi(r,\mu) = \sum_{\ell=0,2,4} L_\ell(\mu)\xi_l(r),$$

$$\xi_0(r) = C_0\xi_R(r),$$

$$\xi_2(r) = C_2\left(\xi_R(r) - \bar{\xi}(r)\right),$$

$$\xi_4(r) = C_4\left(\xi_R(r) + 2.5\bar{\xi}(r) - 3.5\bar{\bar{\xi}}(r)\right),$$

$$\mu = r_{par}/|\vec{r}|$$

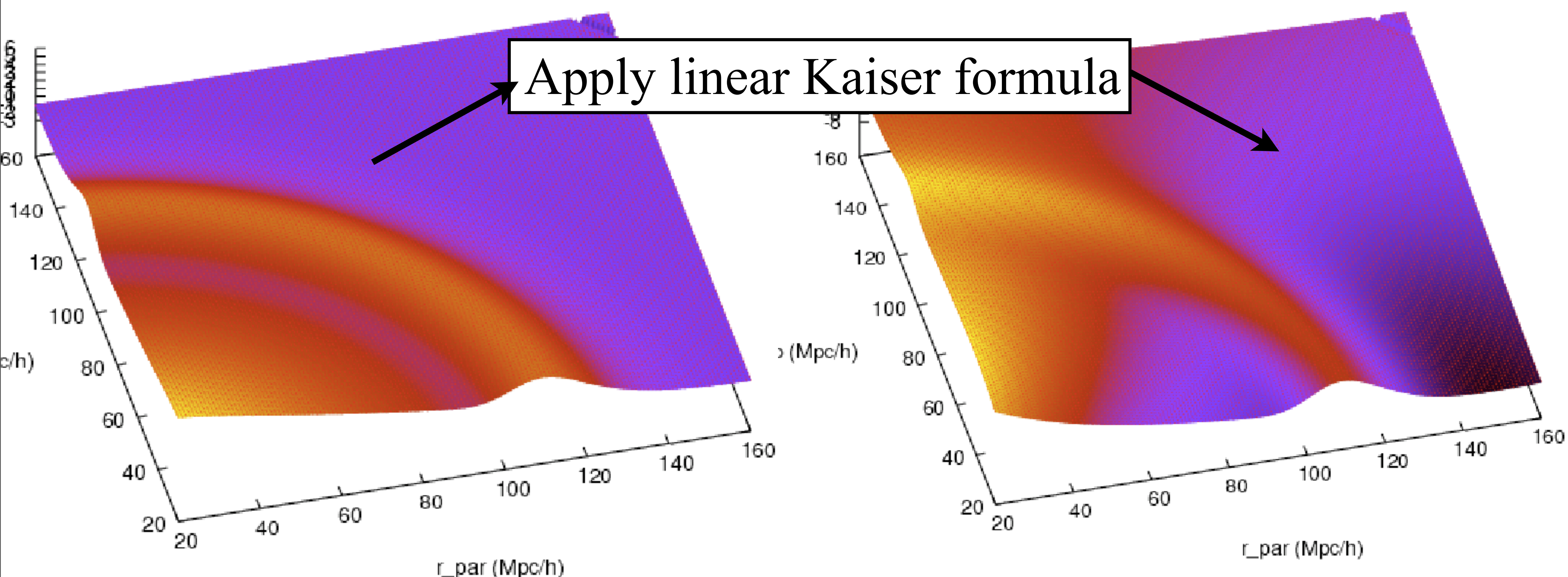
$$C_i = f_i(\beta)$$

$$\beta = dln\delta/dlna = \Omega_m^{0.6}$$

Lyman Alpha Forest: what can it do?

No z-space distortion

z-space distortions



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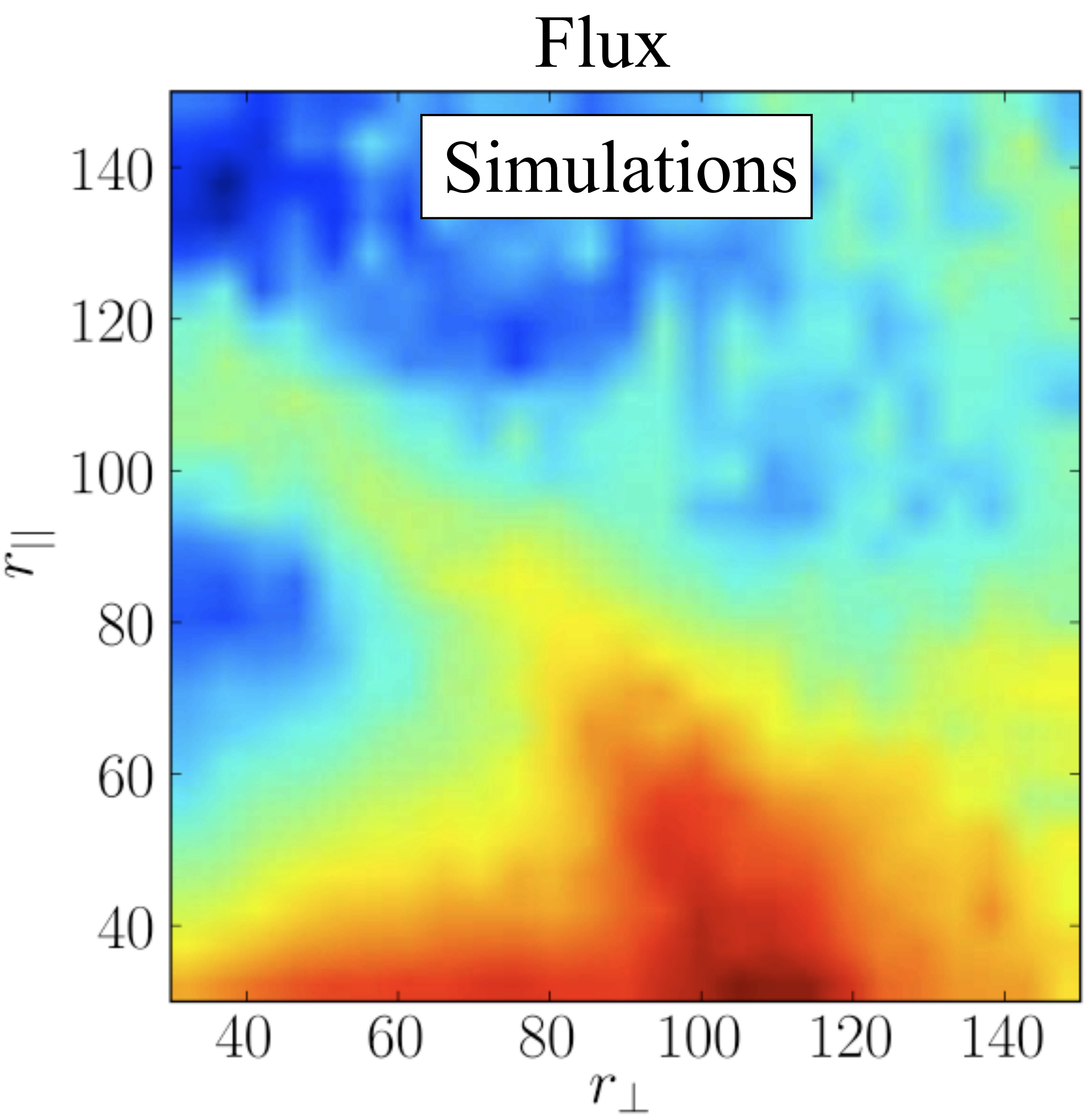

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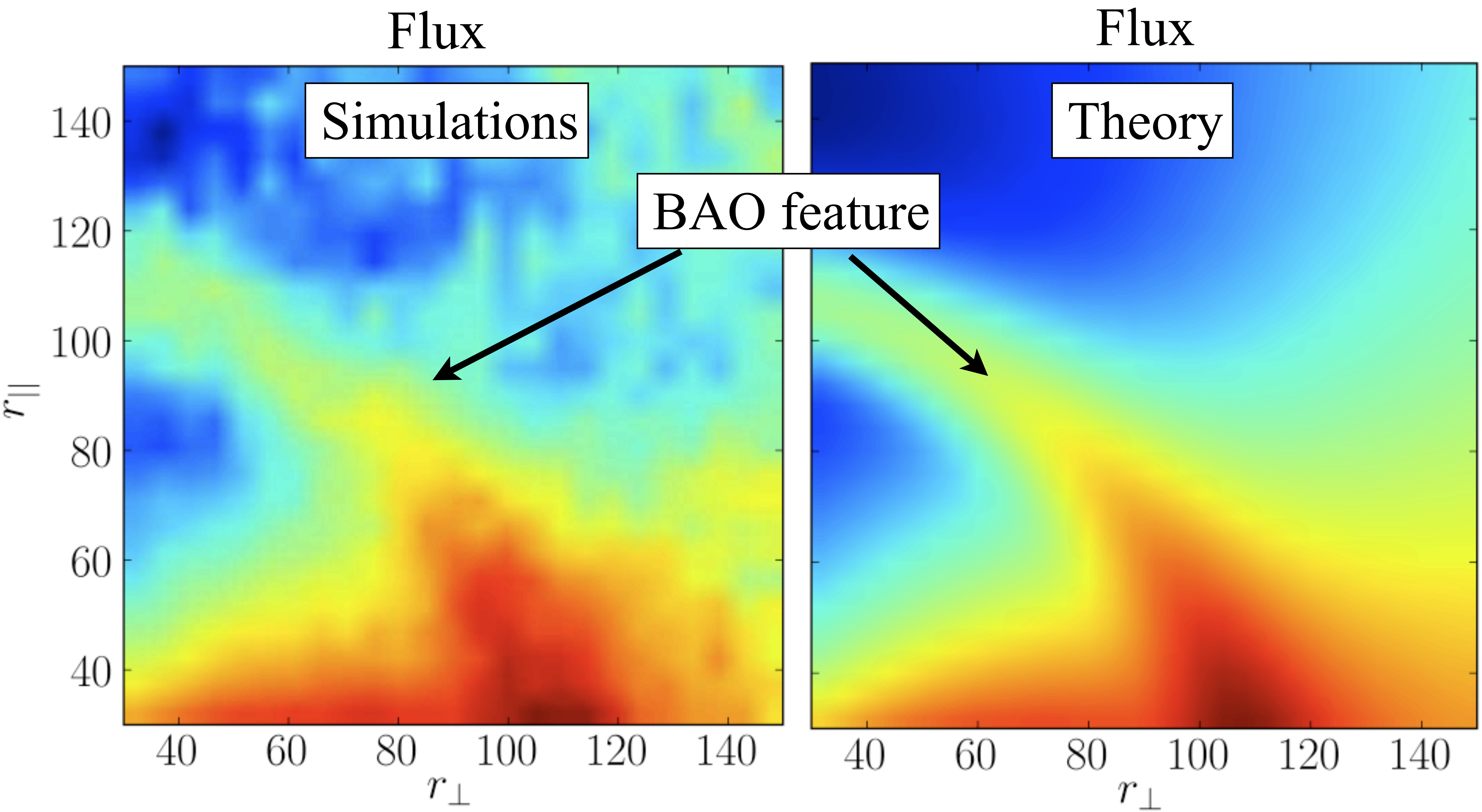

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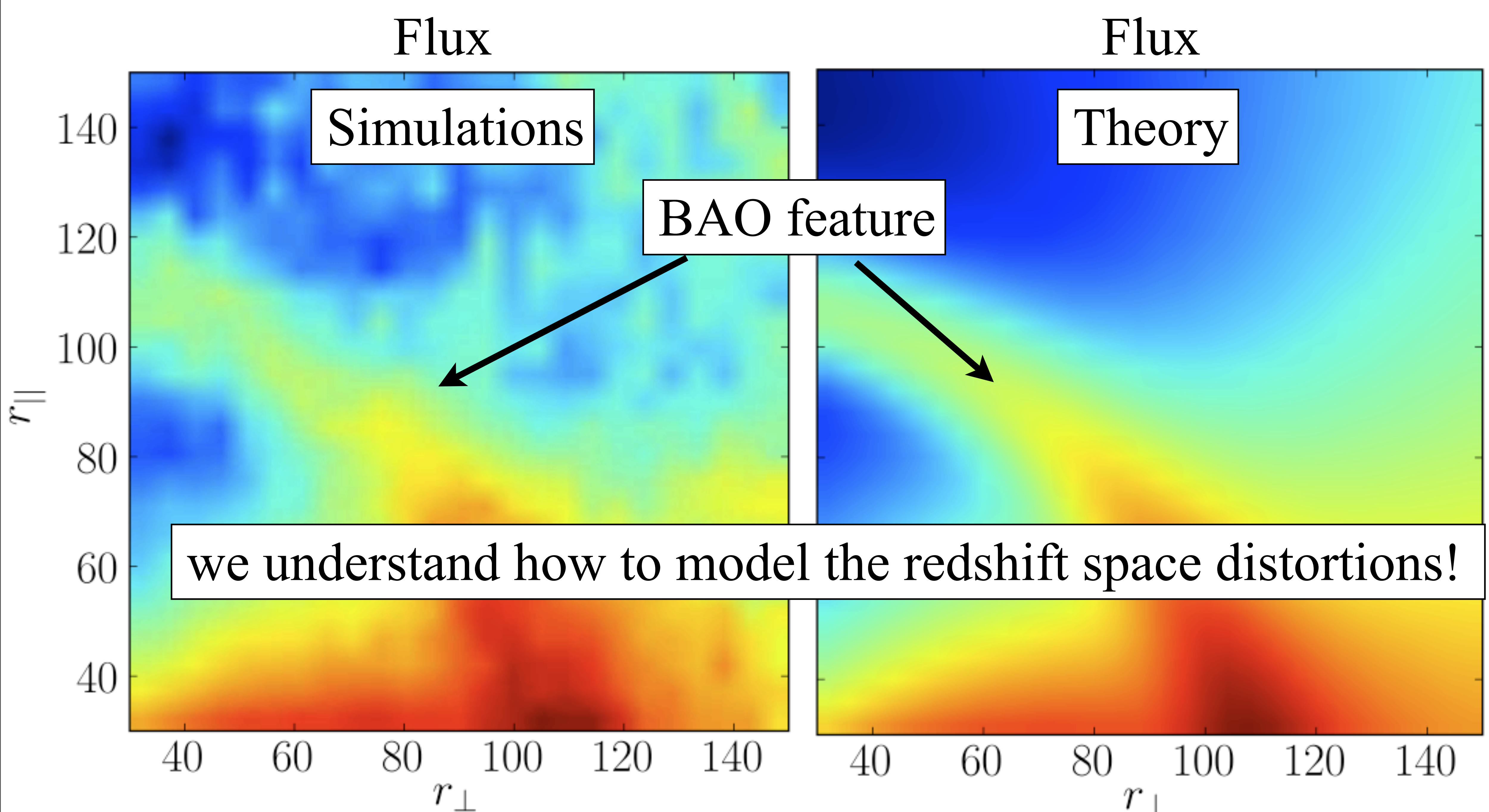
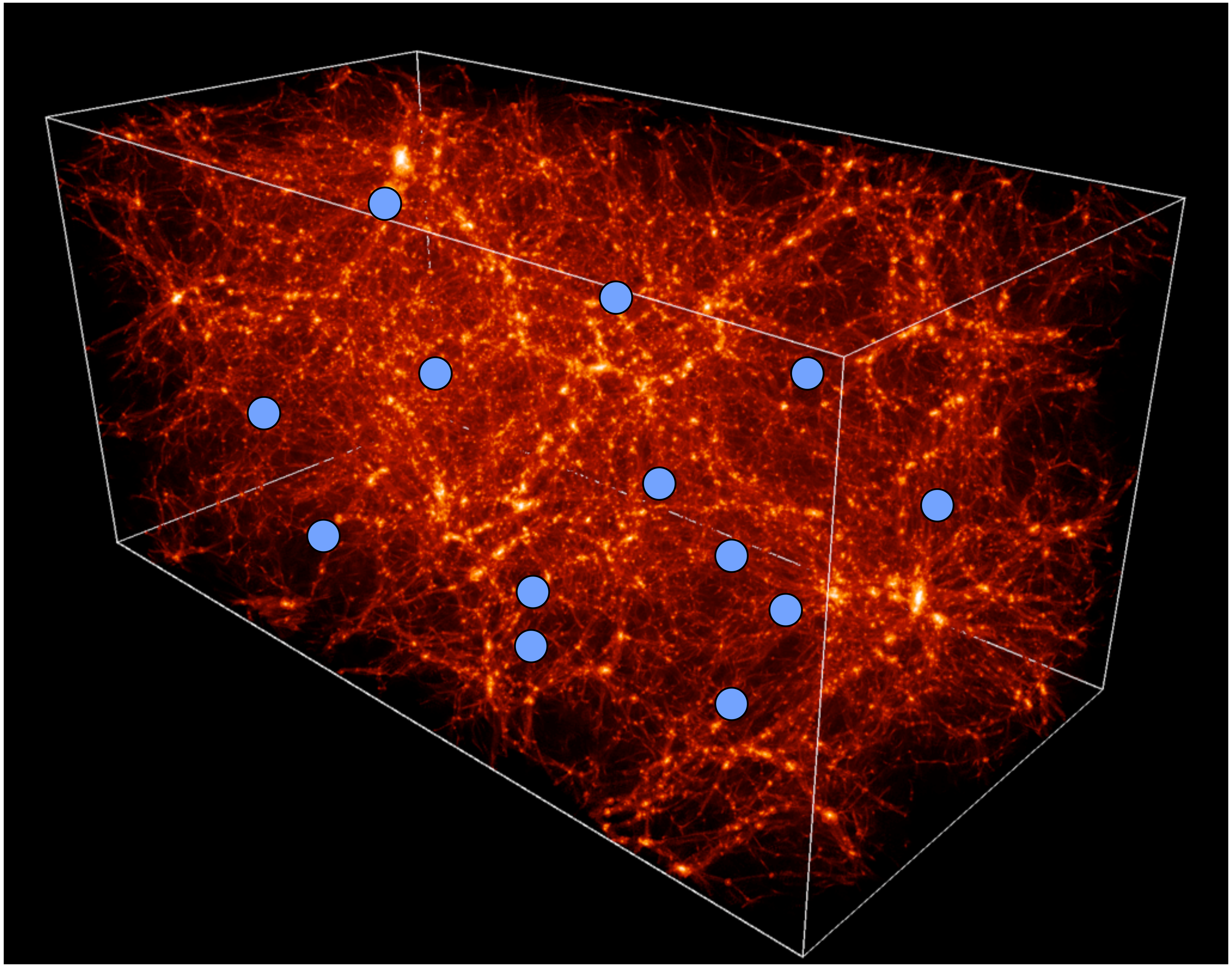


Slosar, SH, White & Louis (2009)

Possible Systematics

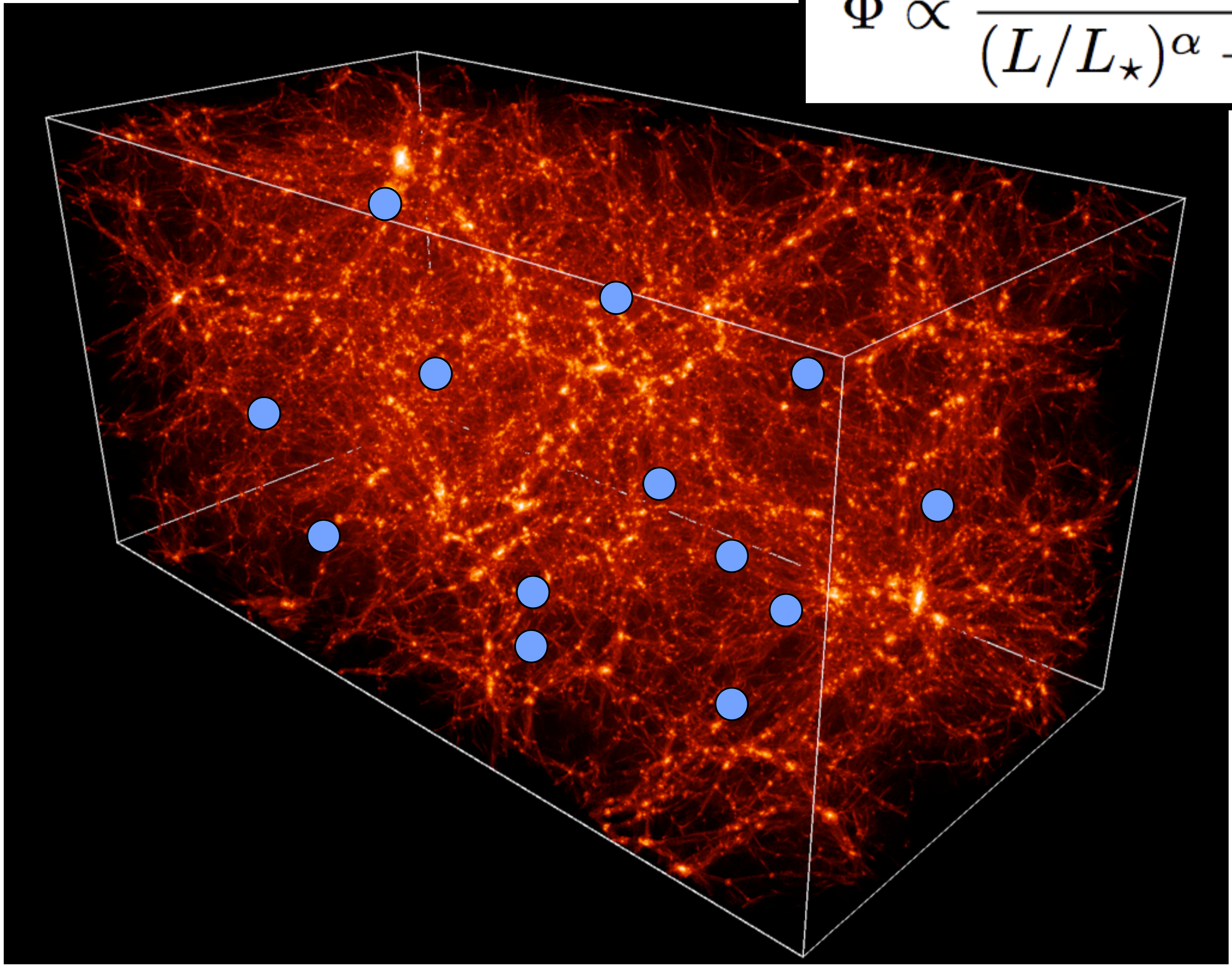
- UV background fluctuations
- Metal Line contaminations
- Continuum subtractions
- Other IGM physics? ...

Possible Systematics: UV background fluctuations



Possible Systematics: UV background fluctuations

$$\Phi \propto \frac{1}{(L/L_\star)^\alpha + (L/L_\star)^\beta}$$



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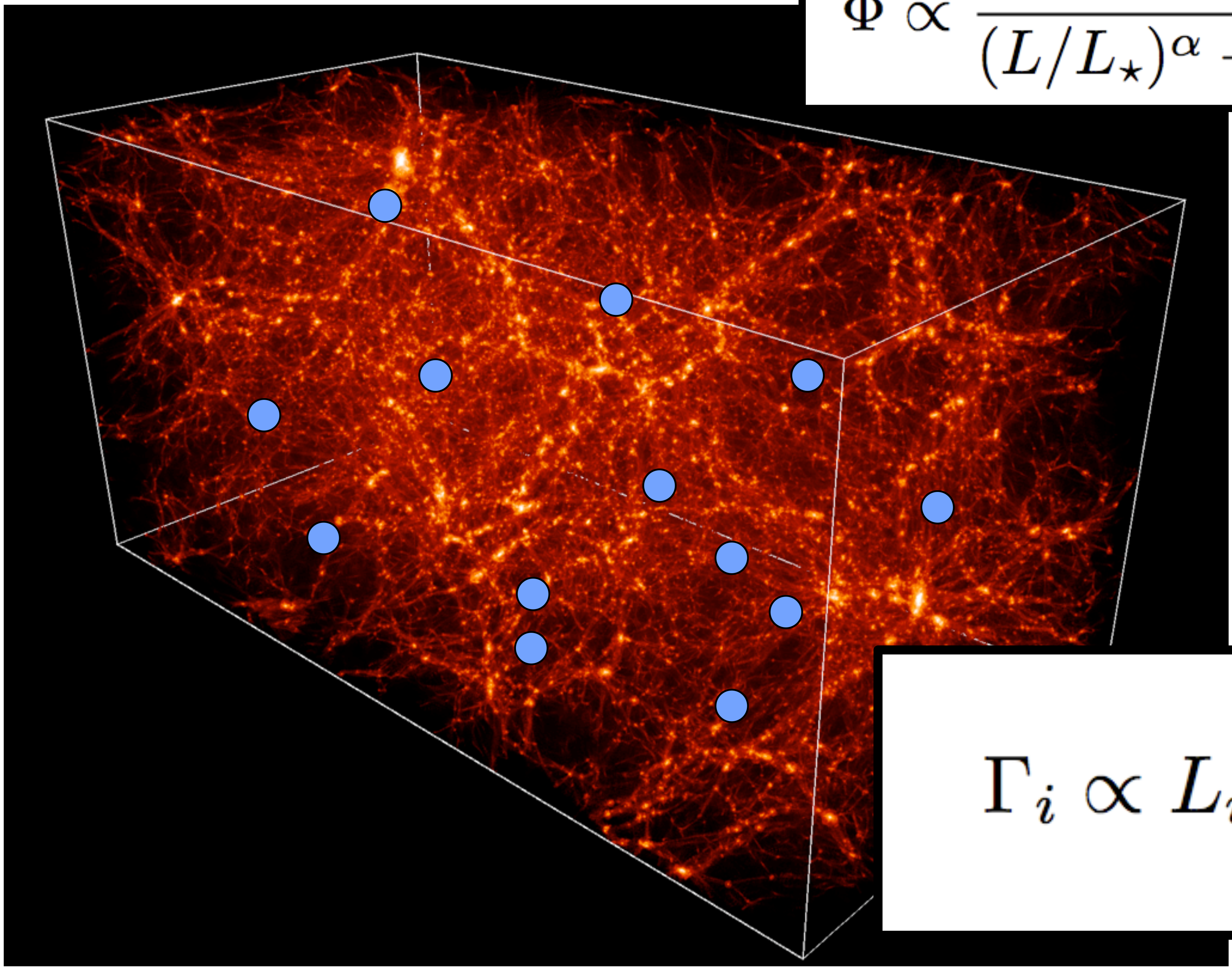
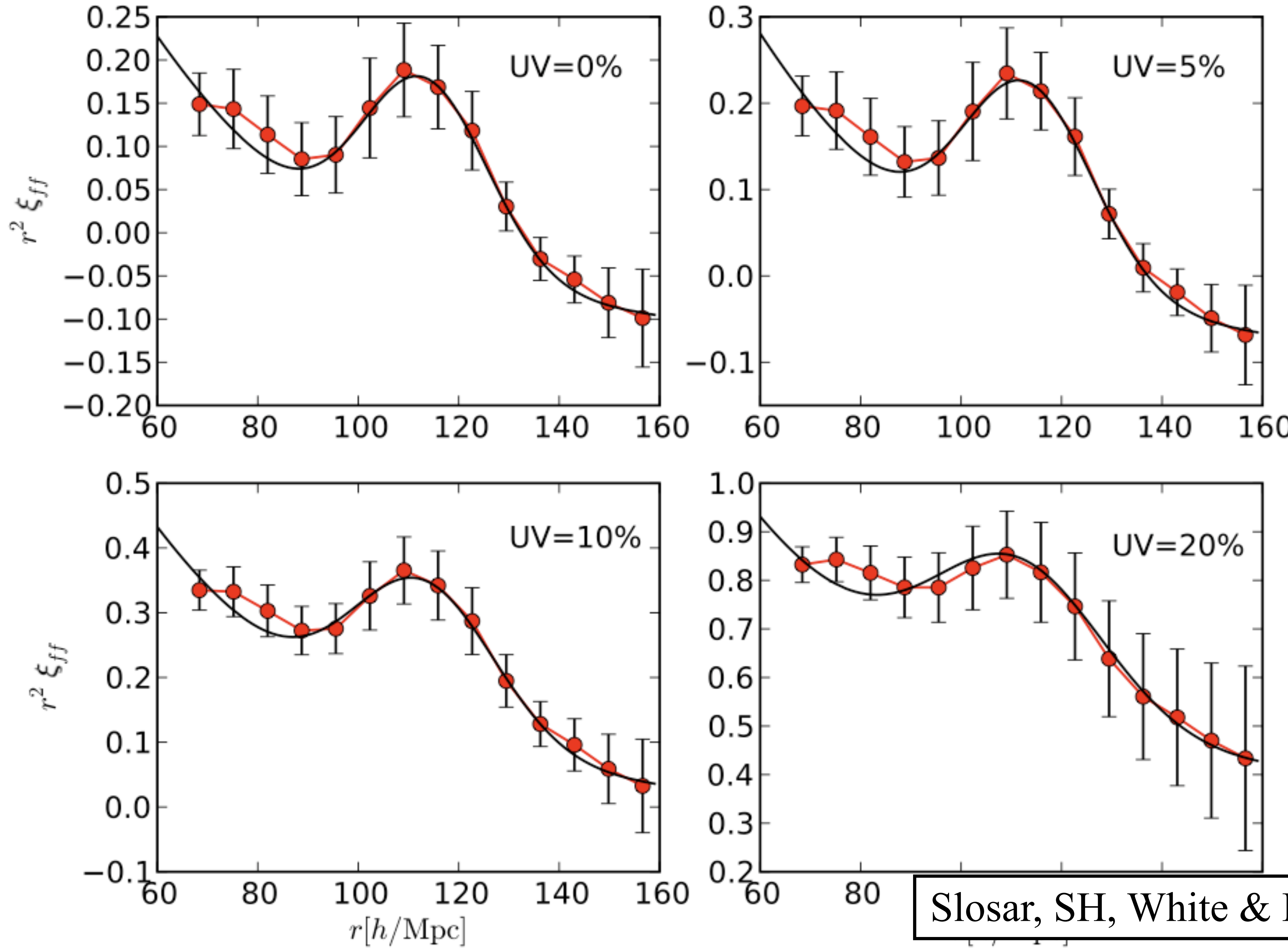


$$\Phi \propto \frac{1}{(L/L_\star)^\alpha + (L/L_\star)^\beta}$$

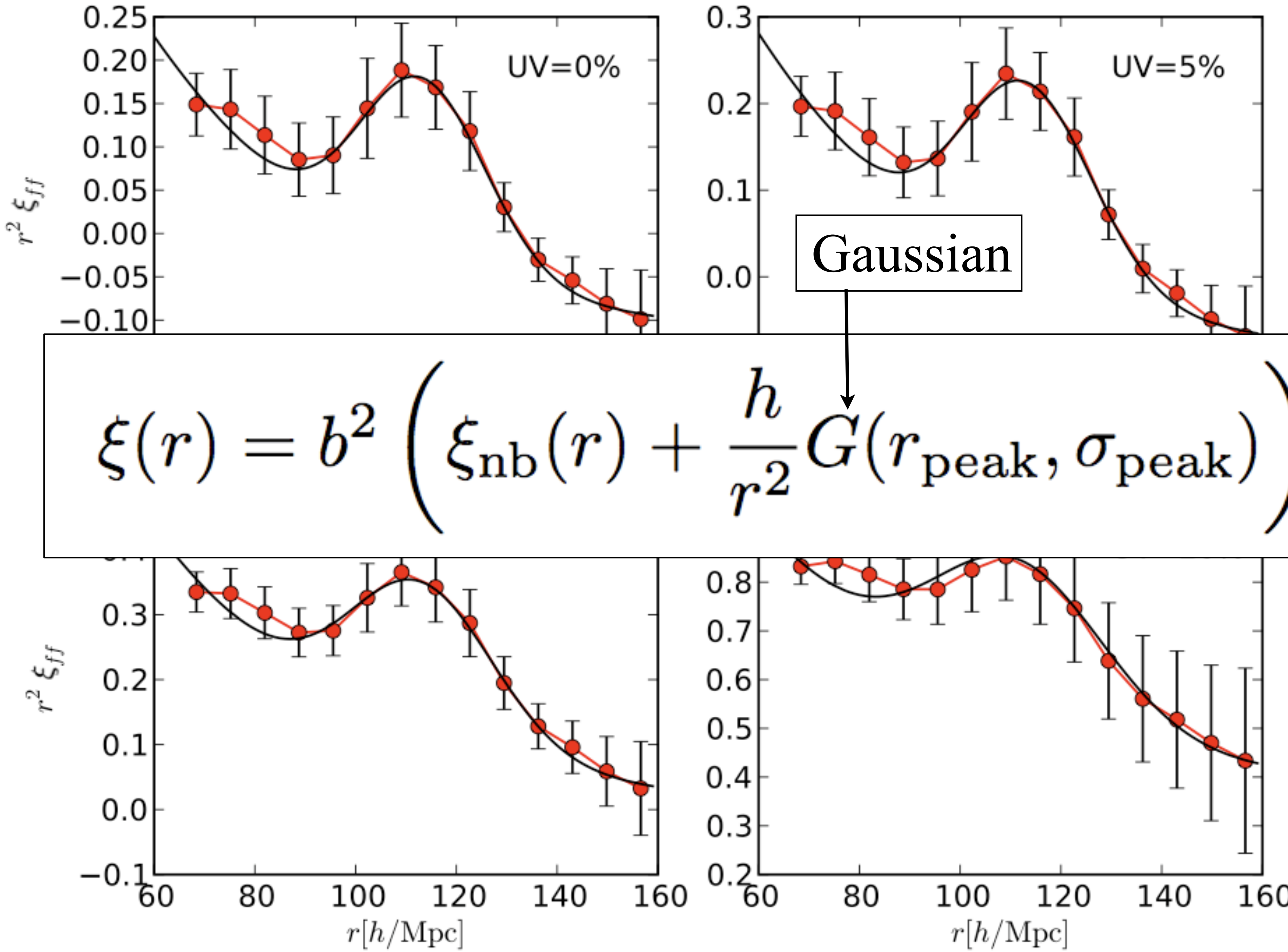
$$\Gamma_i \propto L_i \, \frac{e^{-r_i/r_0}}{4\pi r_i^2}$$

Possible Systematics: UV background fluctuations



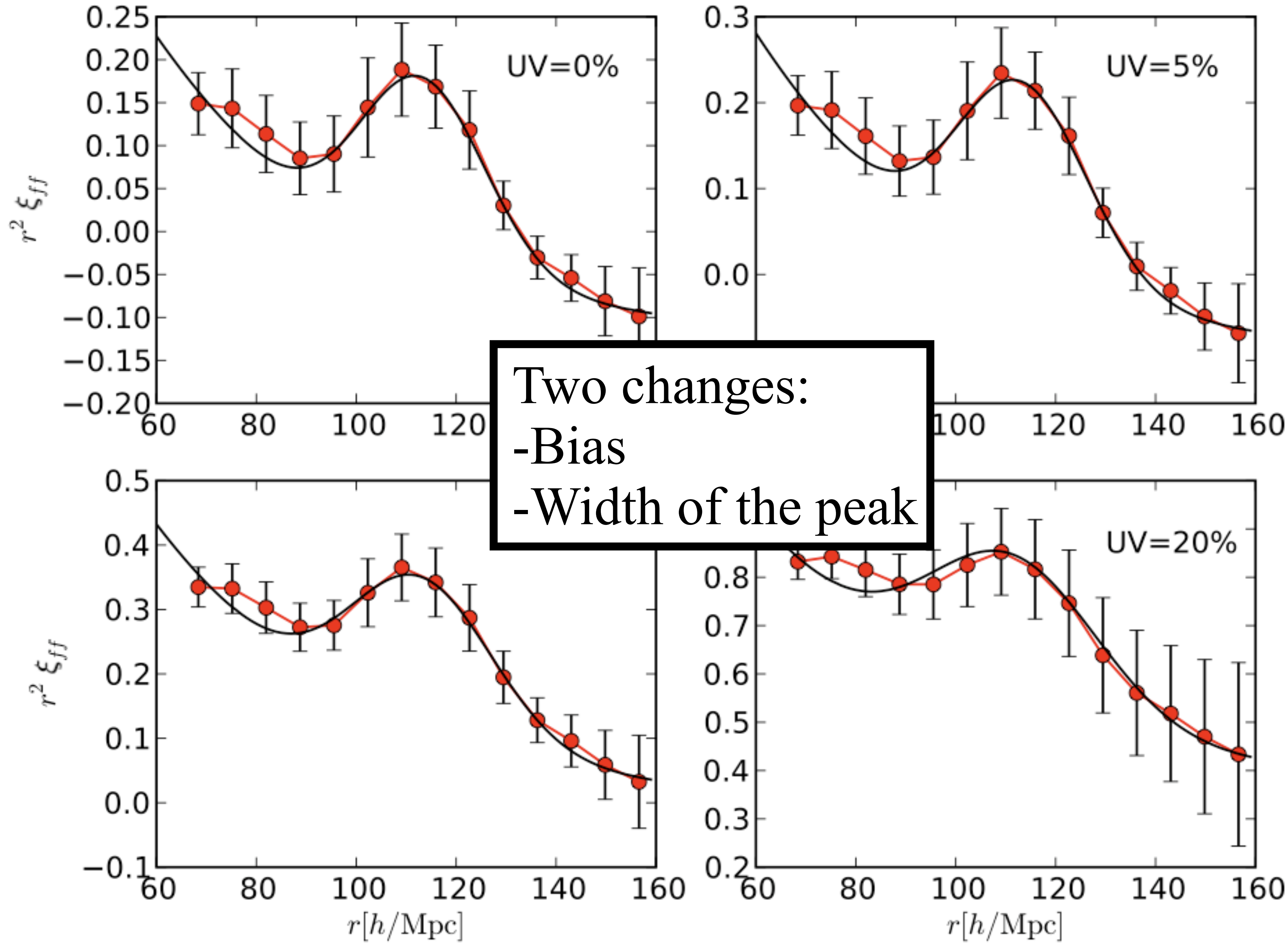
Slosar, SH, White & Louis (2009)

Possible Systematics: UV background fluctuations



$$\xi(r) = b^2\left(\xi_{\rm nb}(r) + \frac{h}{r^2}\overset{\text{Gaussian}}{G}(r_{\rm peak},\sigma_{\rm peak})\right) +$$

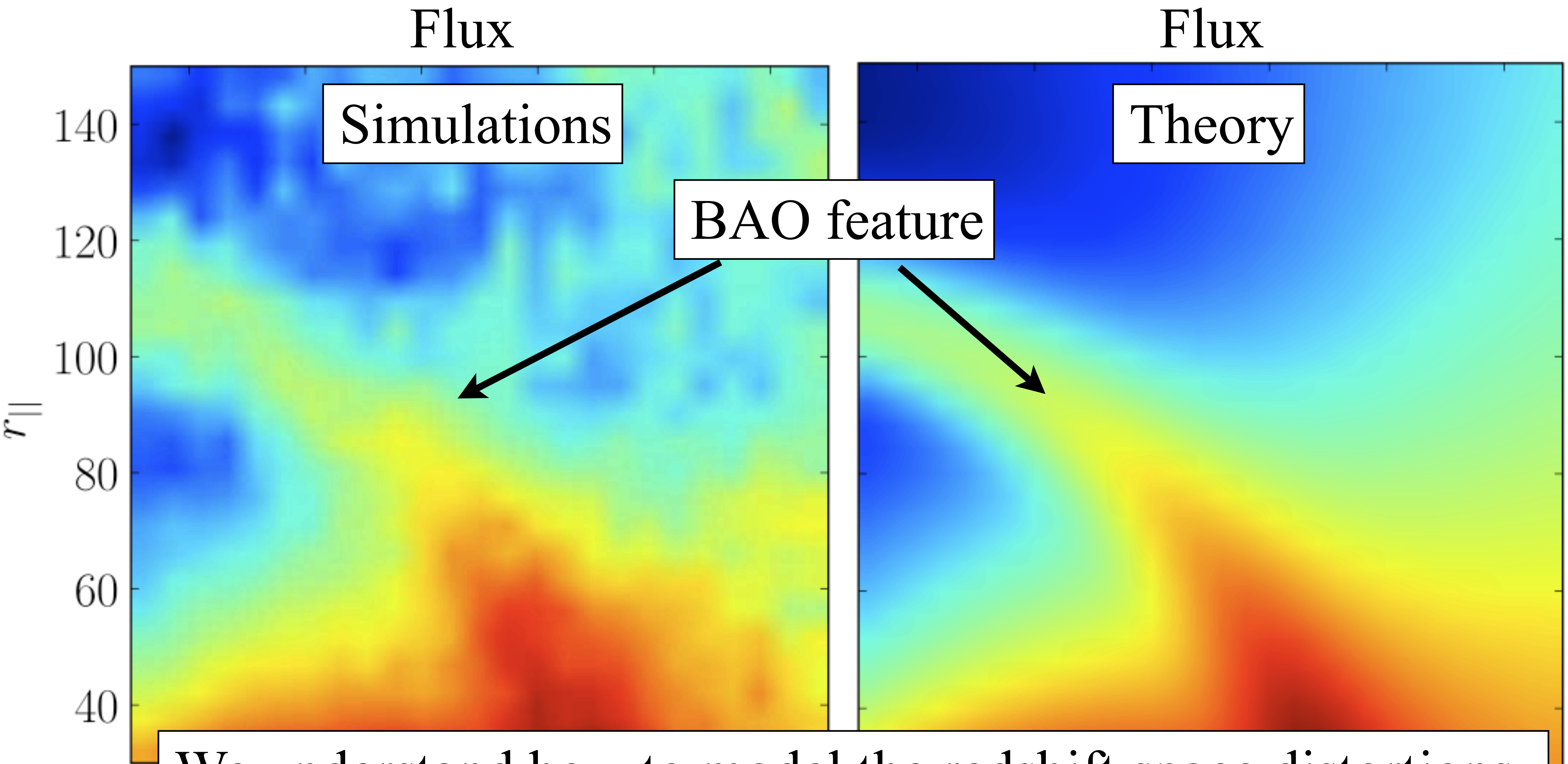
Possible Systematics: UV background fluctuations



Two changes:
-Bias
-Width of the peak

Lyman Alpha Forest: what can it do?

- **Dark Energy via Baryon Acoustic Oscillations**



We understand how to model the redshift space distortions, and approximately what happens when we include systematics such as UV background fluctuations.

Lyman Alpha Forest: what can it do?

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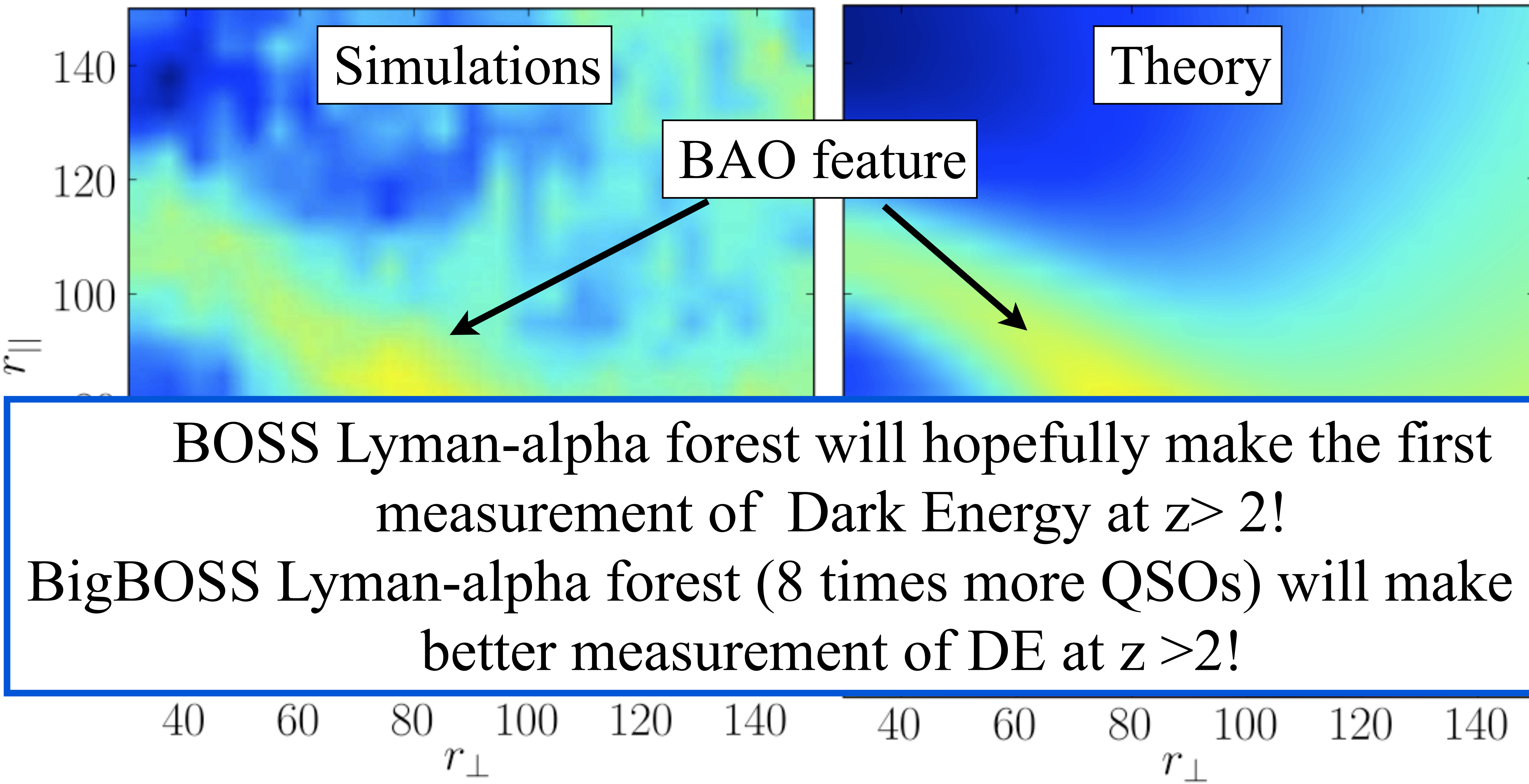

BOSS Lyman-alpha forest will hopefully make the first measurement of Dark Energy at z> 2!
BigBOSS Lyman-alpha forest (8 times more QSOs) will make even better measurement of DE at z >2!

Lyman Alpha Forest: what can it do?

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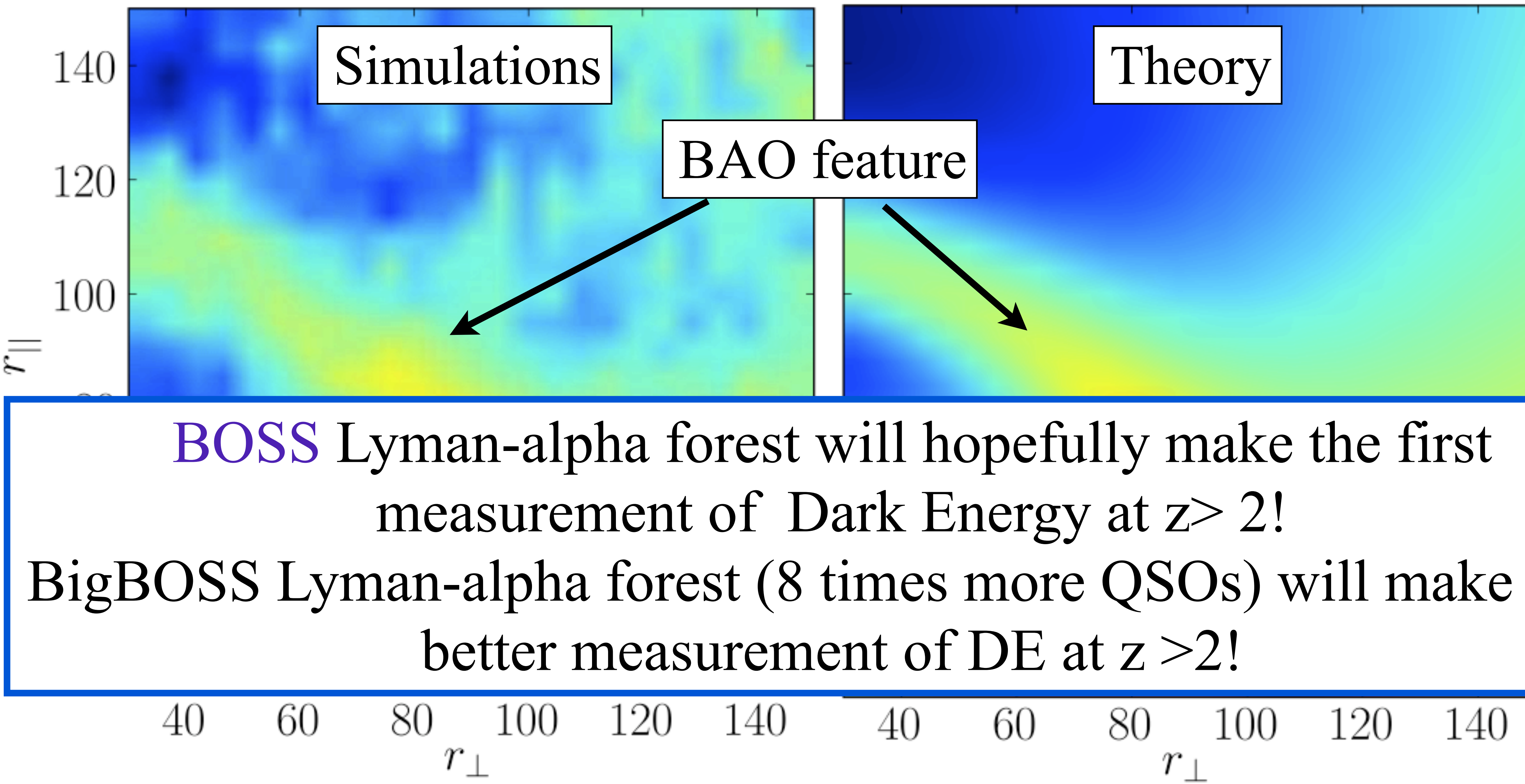

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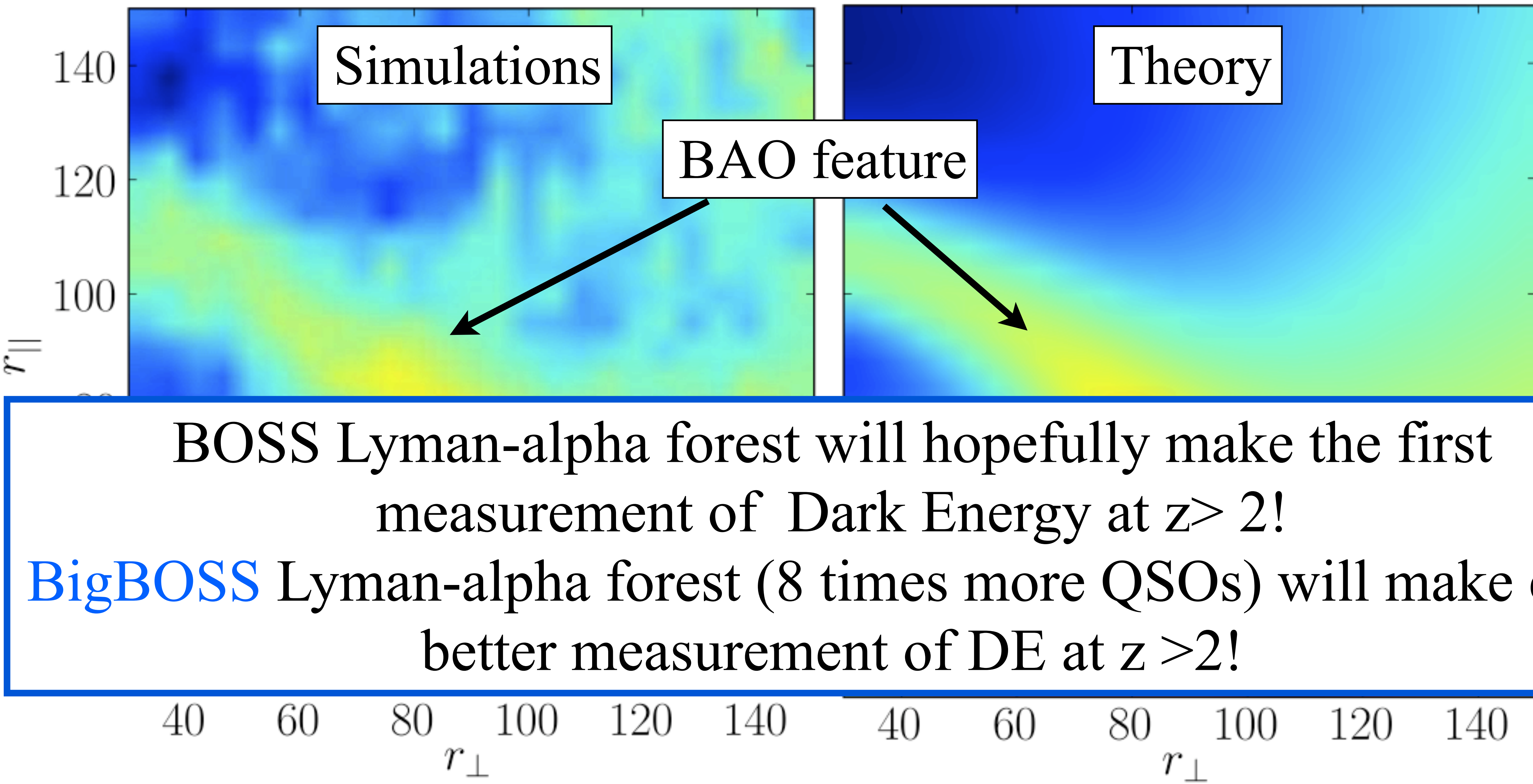

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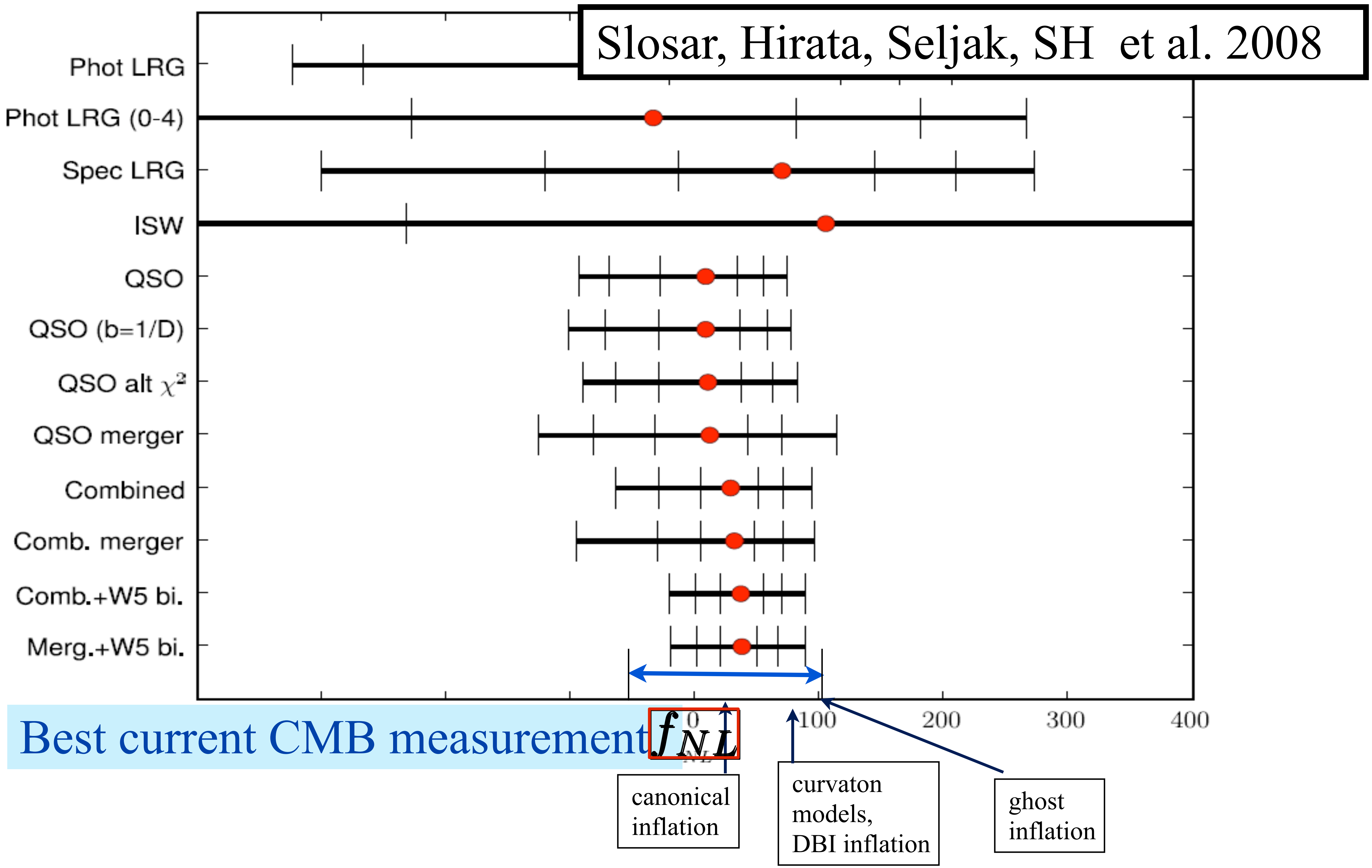
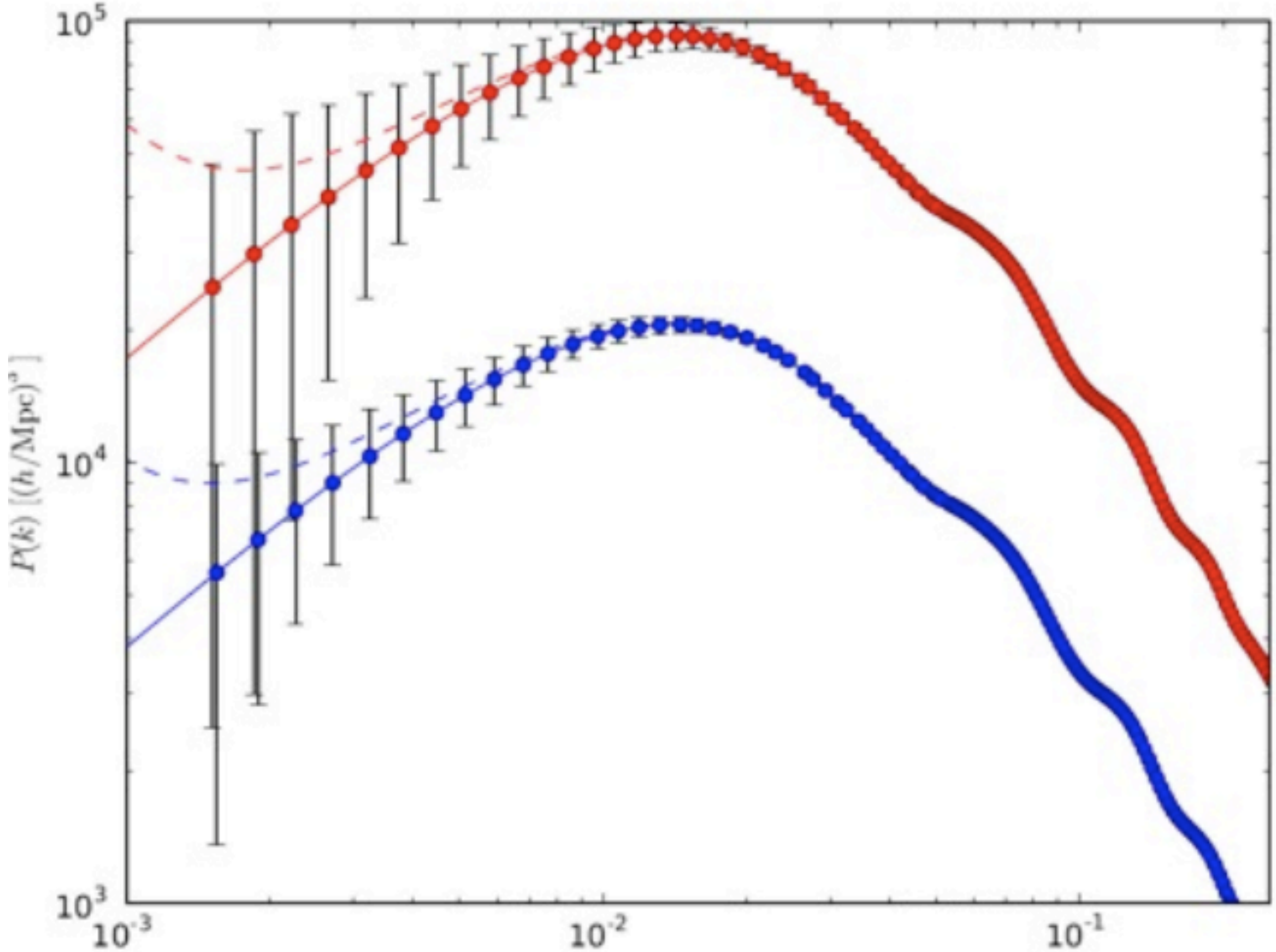
Outline

- Motivations
- Introduction (What is Lyman-alpha forest?)
- What can you do with Lyman-alpha forest?
  - —Baryon Acoustic Oscillations
    - Dark Energy
  - —Scale Dependent Bias
    - Primordial Non-gaussianities (f_nl)
- Conclusion

Lyman Alpha Forest: what can it do?
—Non-gaussianities in Early Universe



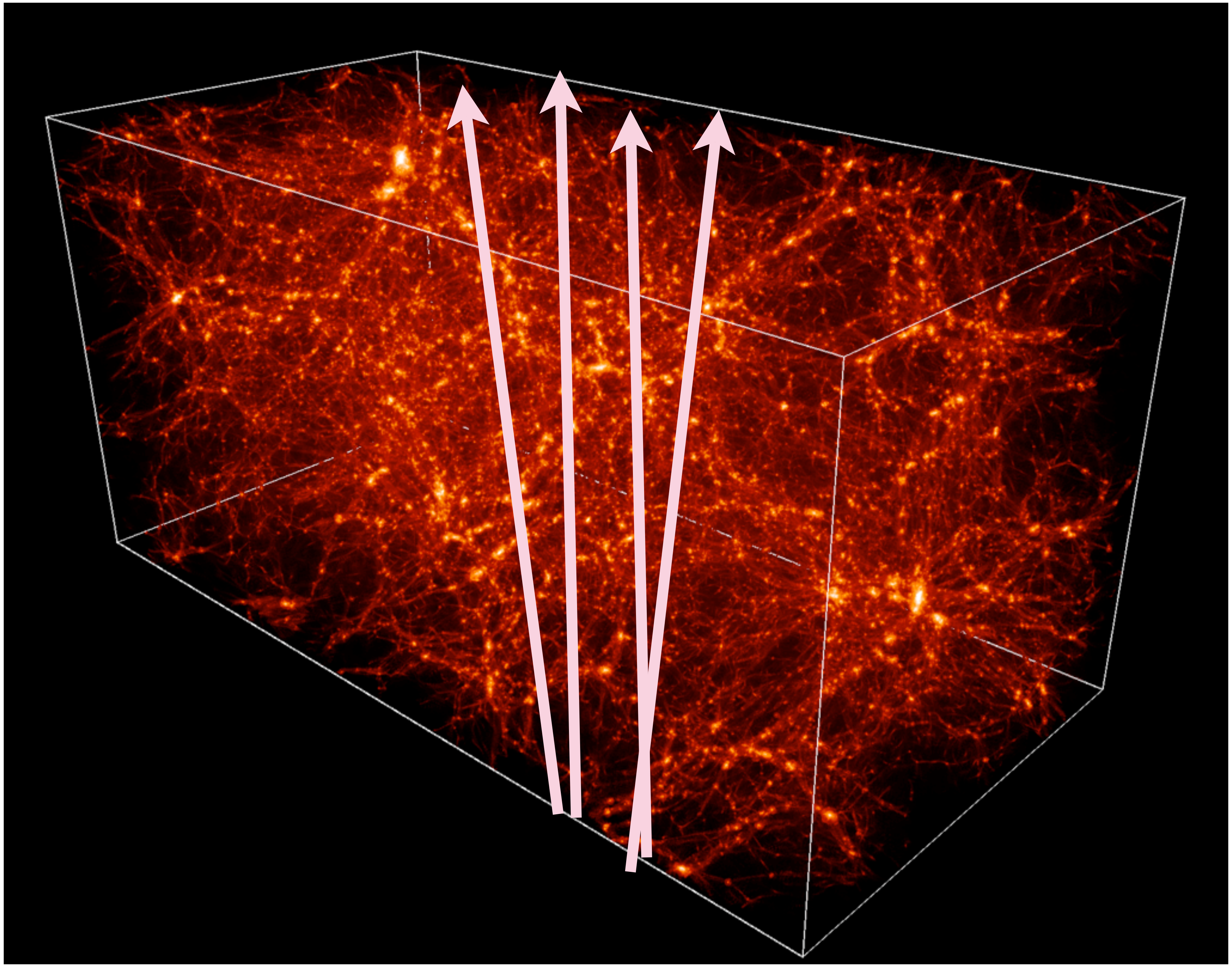
P(k) (Mpc/h)^3



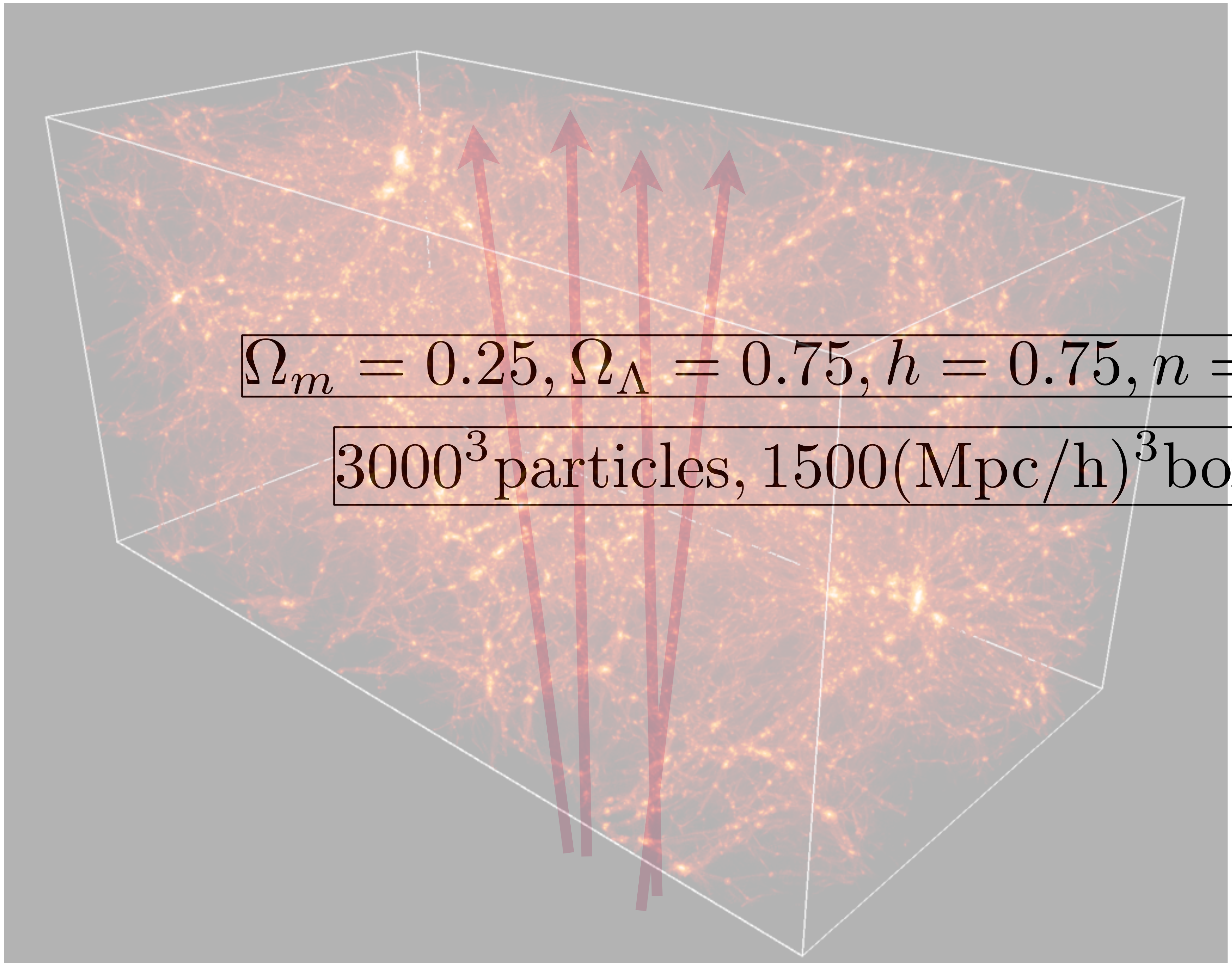
k (h/Mpc)

Courtesy slide from Anze Slosar

Lyman Alpha Forest: what can it do?



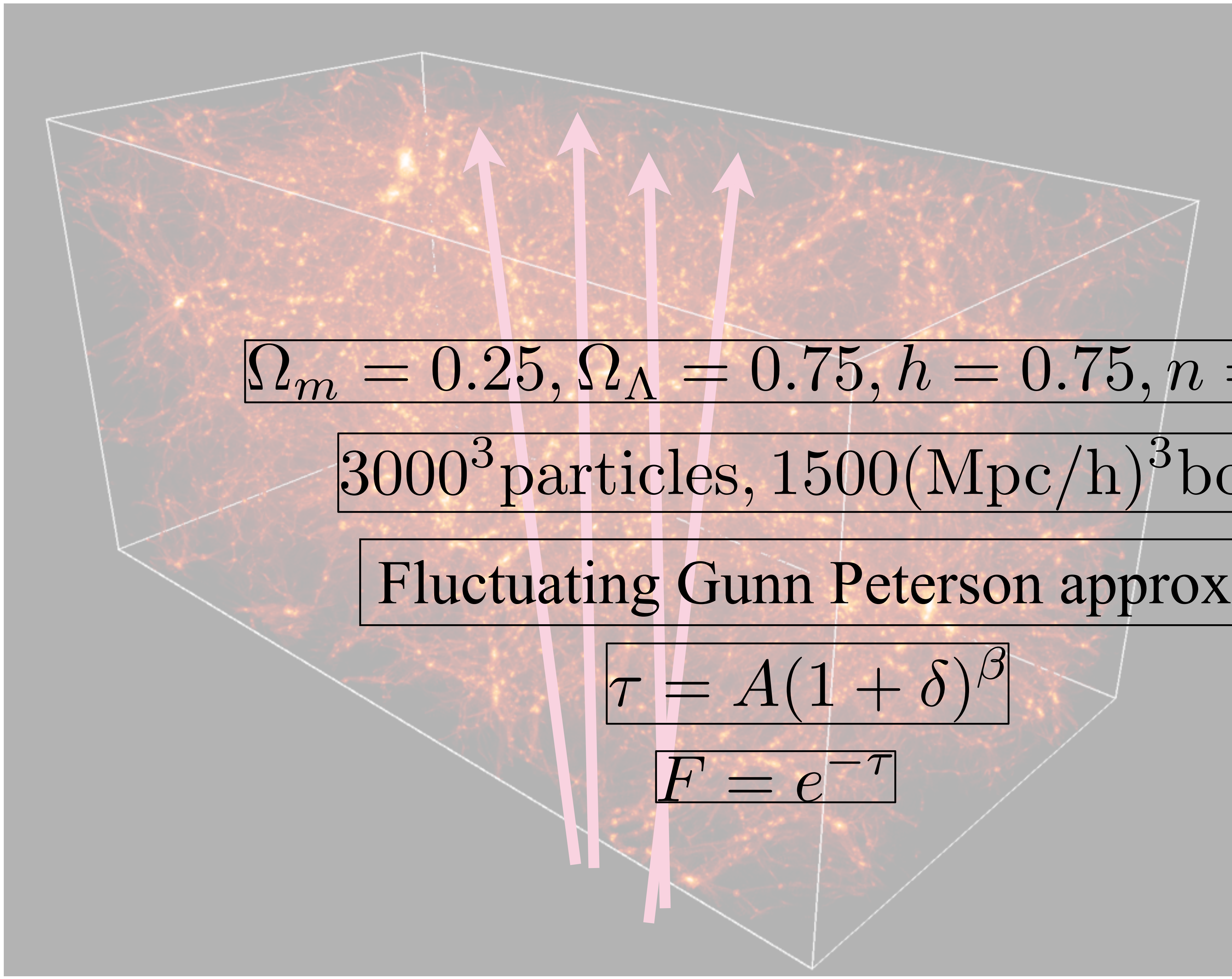
Lyman Alpha Forest: what can it do?



$\boxed{\Omega_m = 0.25, \Omega_\Lambda = 0.75, h = 0.75, n = 0.97, \sigma_8 = 0.8}$

$\boxed{3000^3\text{particles}, 1500(\text{Mpc/h})^3\text{box}, 3000^3\text{grid}}$

Lyman Alpha Forest: what can it do?



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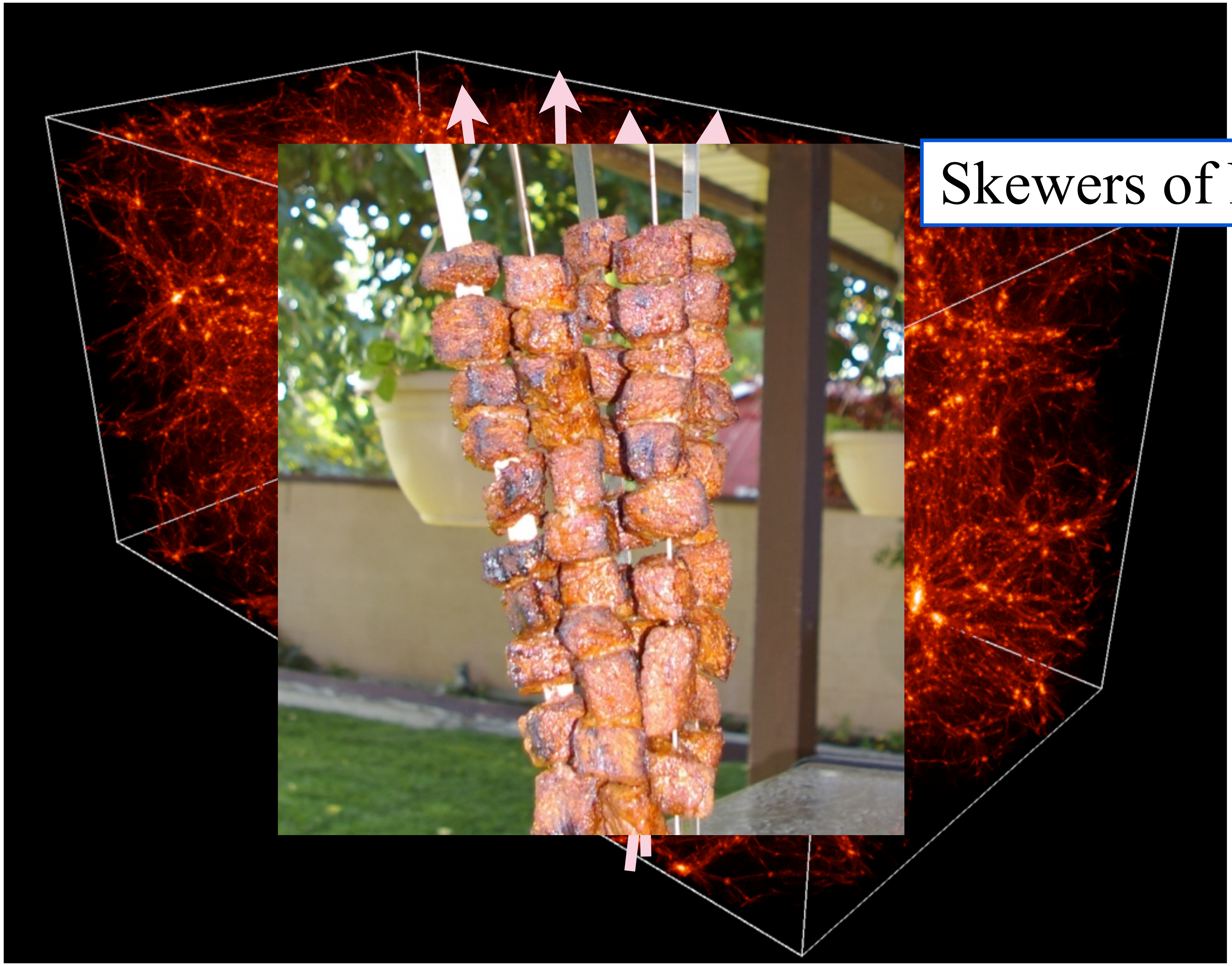
Fluctuating Gunn Peterson approximation

$$\boxed{\tau = A(1+\delta)^\beta}$$

$$\boxed{F = e^{-\tau}}$$

Lyman Alpha Forest: what can it do?

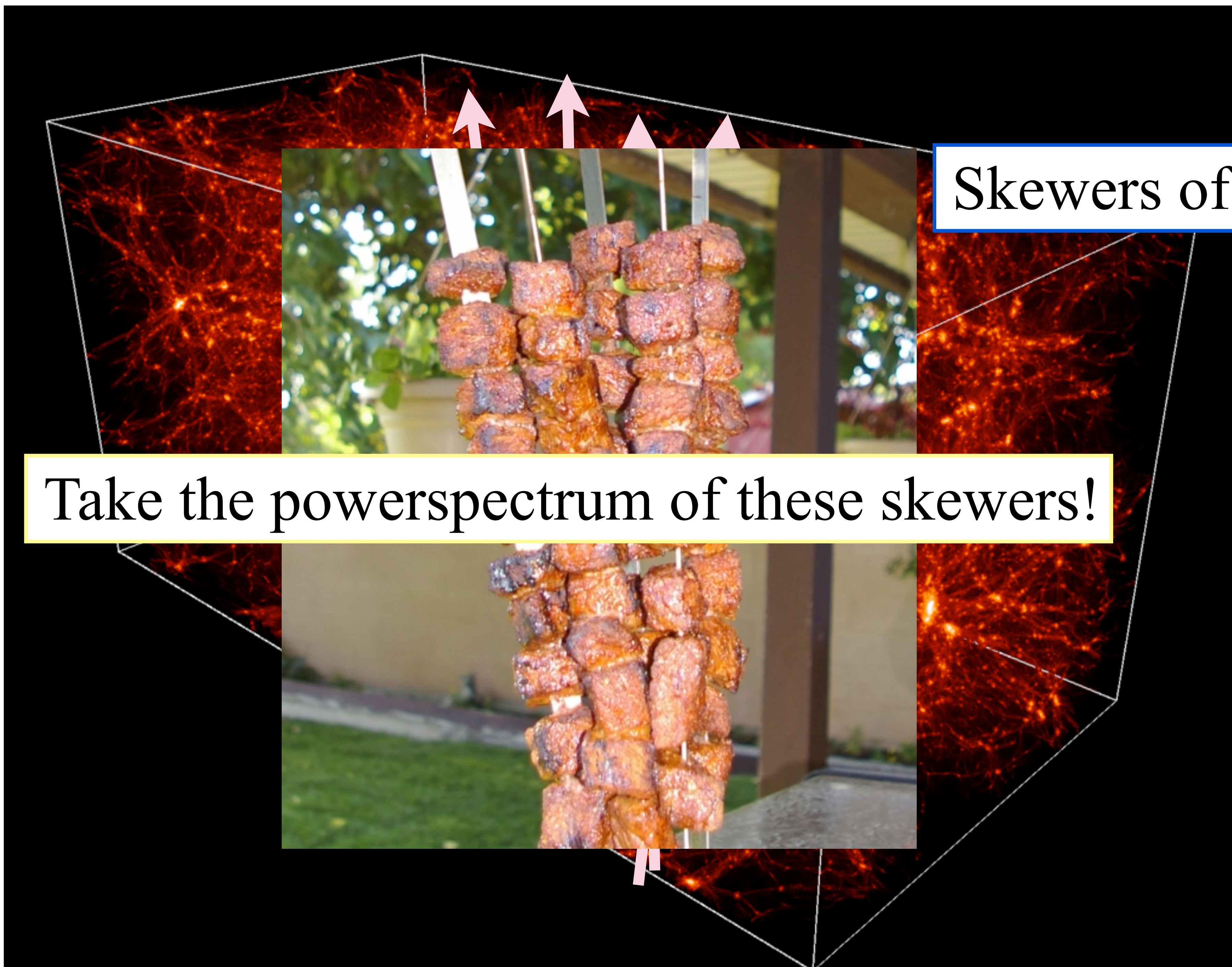
- **Dark Energy via Baryon Acoustic Oscillations**



Skewers of Neutral Hydrogen

Lyman Alpha Forest: what can it do?

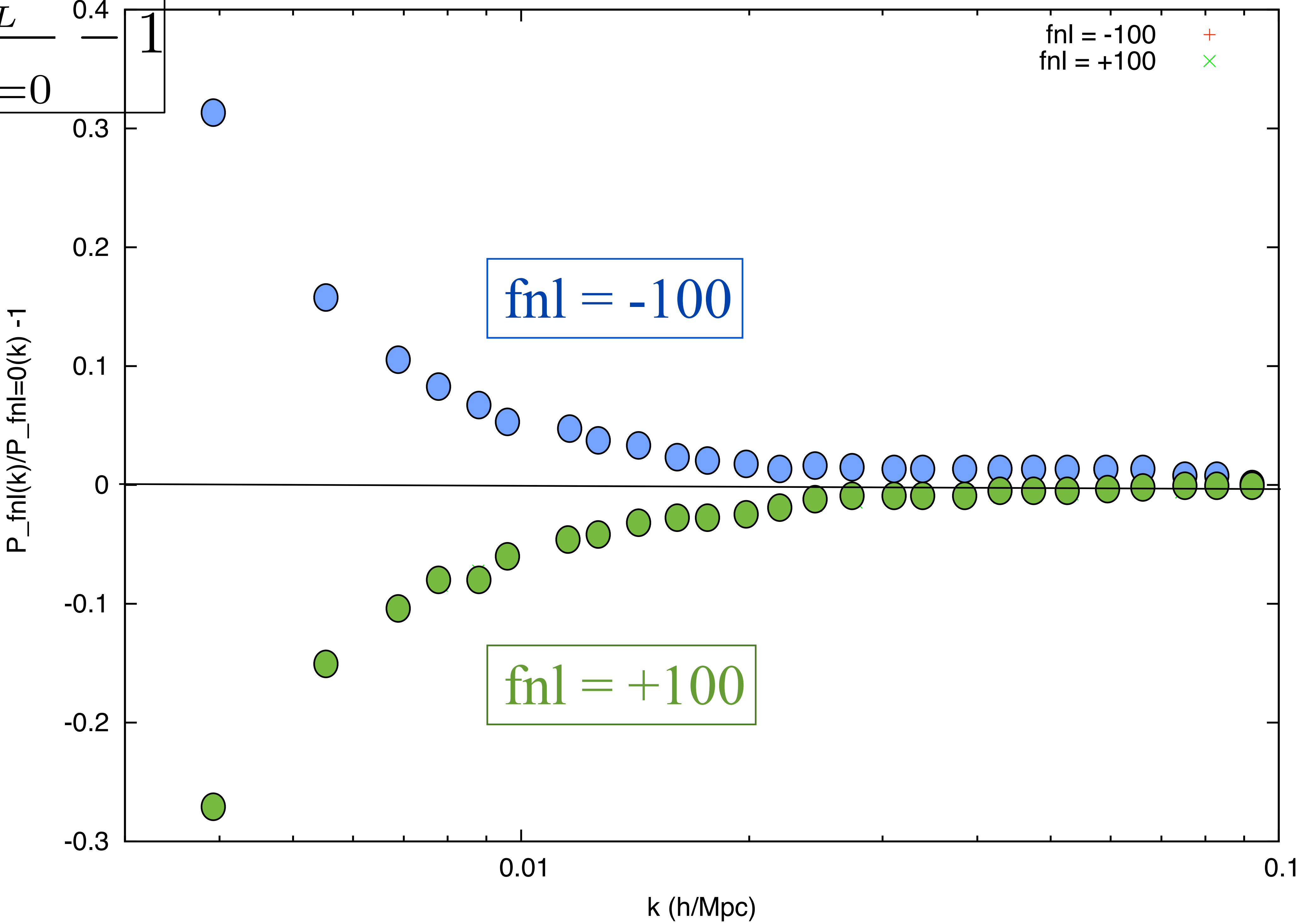
- **Dark Energy via Baryon Acoustic Oscillations**



What can we do with Lya and fnl?

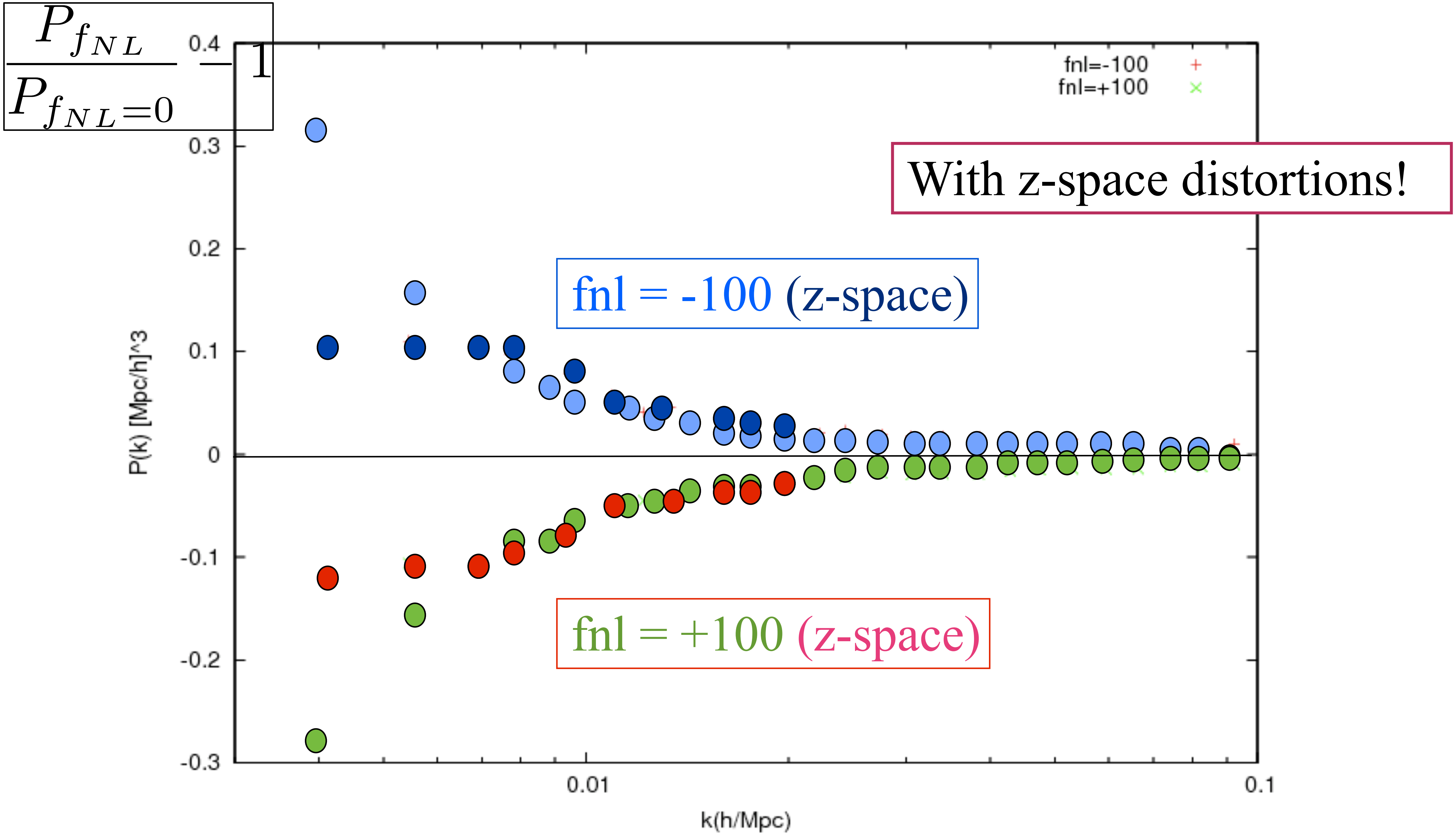
Berkeley Lab

$$\frac{P_{f_{NL}}}{P_{f_{NL}=0}} - 1$$



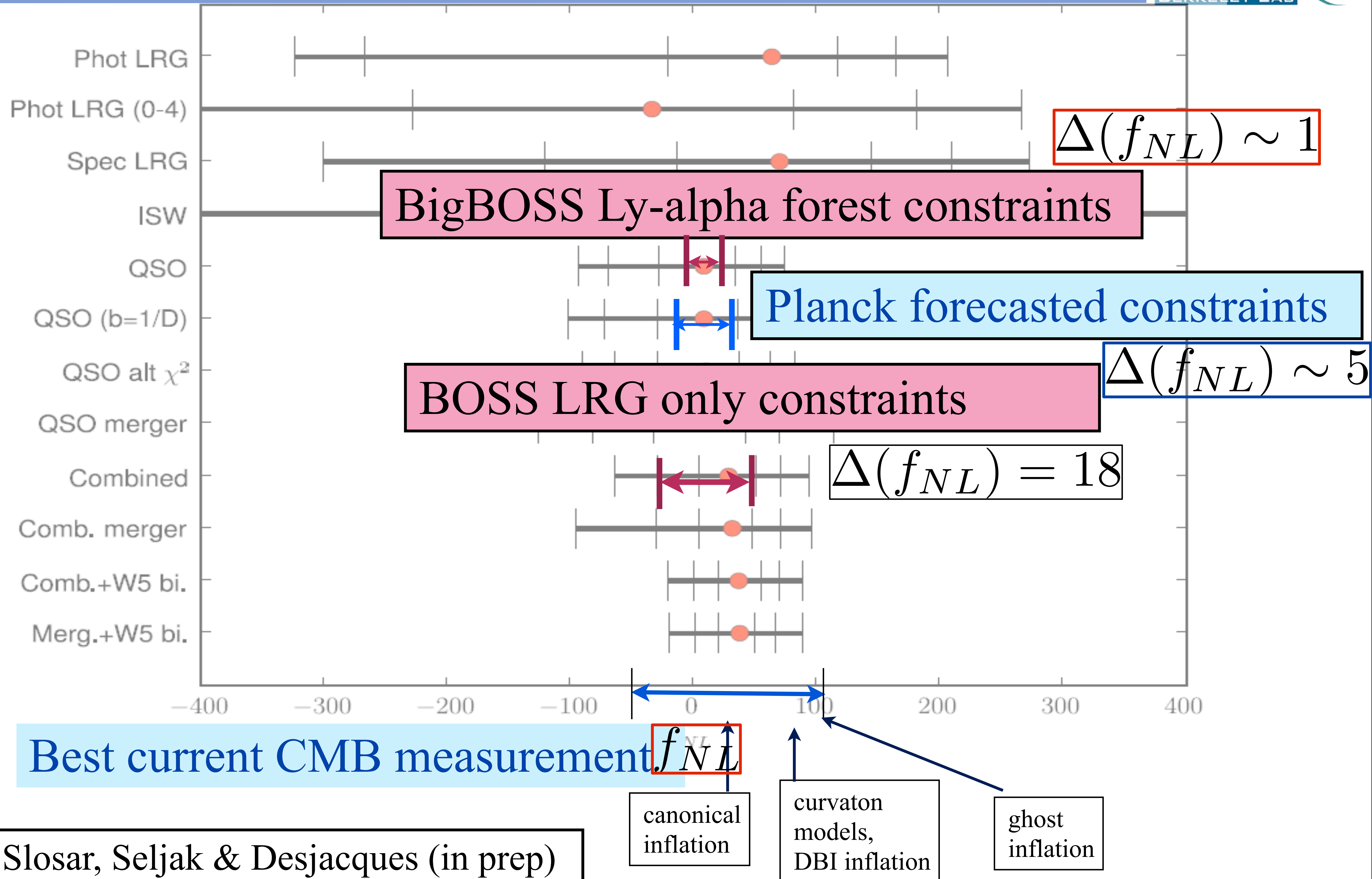
SH, Slosar, Seljak & Desjacques (in prep)

What can we do with Lya and fnl?



SH, Slosar, Seljak & Desjacques (in prep)

What can we do with Lya and fnl?
—Non-gaussianities in Early Universe

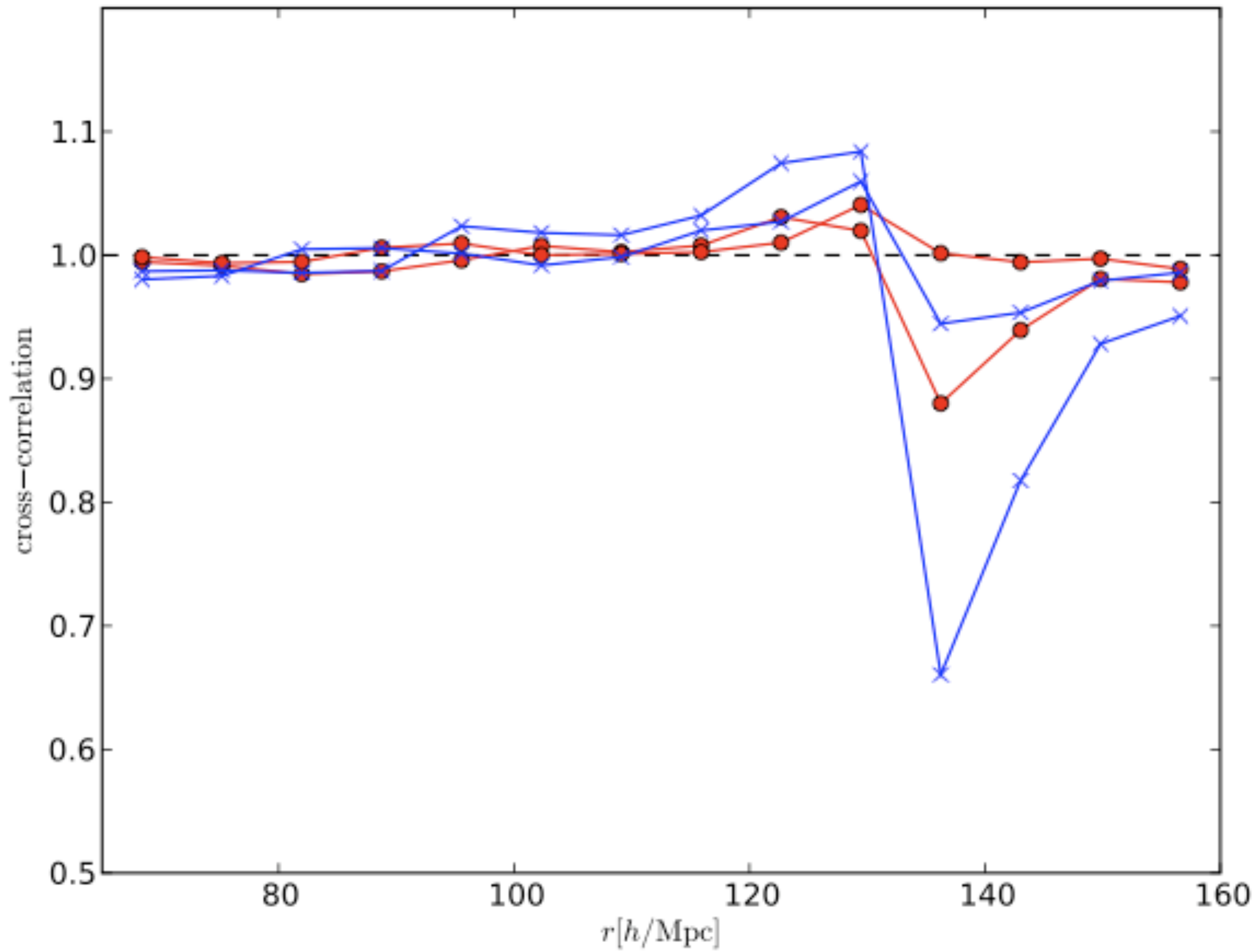


SH, Slosar, Seljak & Desjacques (in prep)

Conclusion

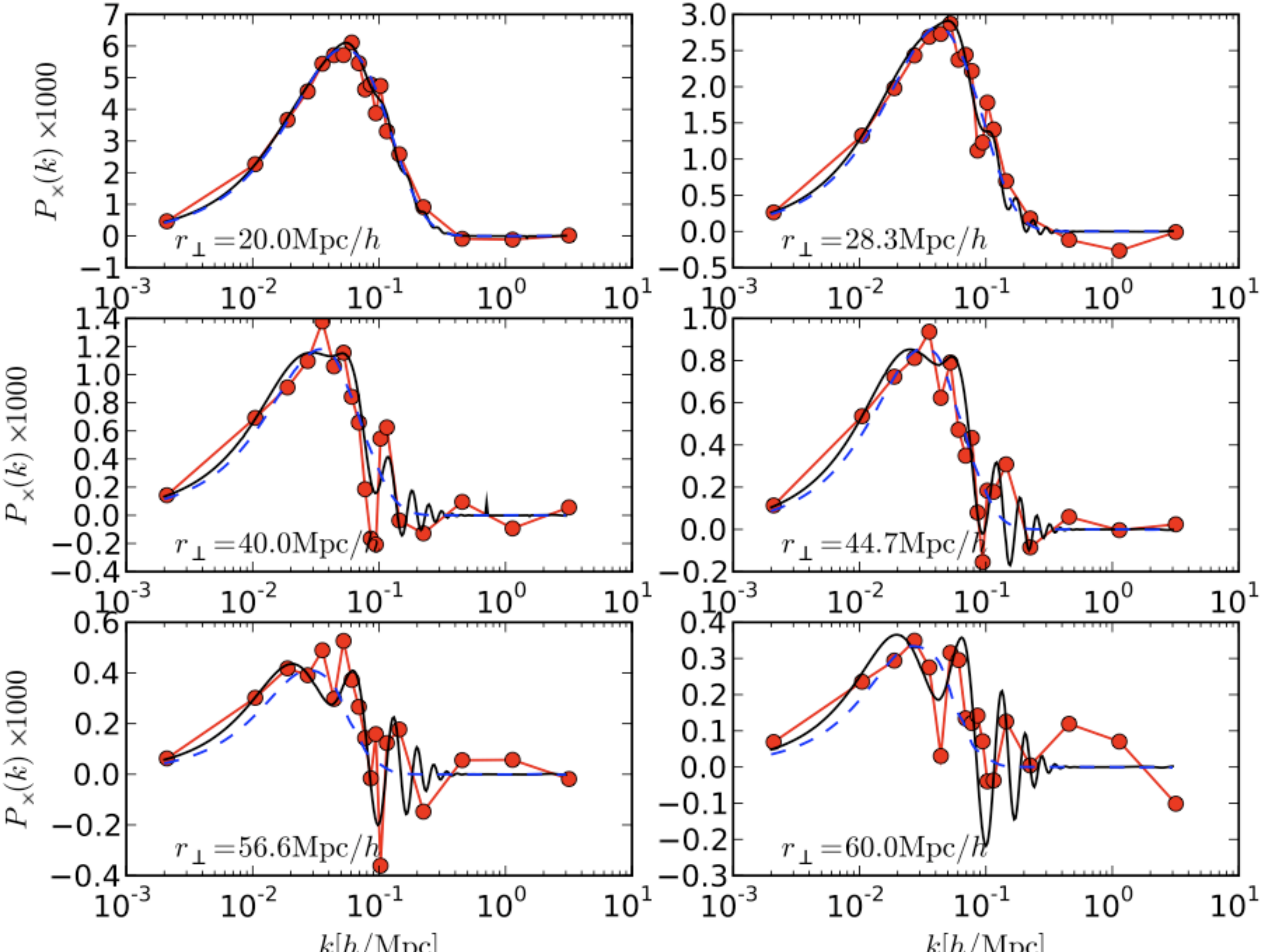
- Lyman-alpha forest in BOSS and BigBOSS will (hopefully) do the following:
  - —Lya BAO to measure Dark Energy at z>2
  - —Lya probes non-gaussianity of the Early Universe
  - —Other applications:
    - Lya P(k) tighten the cosmological constraints
    - temperature density relation in the IGM
    - finding missing baryons at higher z

$$\sqrt{\xi_{lh}^2/\xi_{ll}\xi_{hh}}$$



$$r[h/Mpc]$$

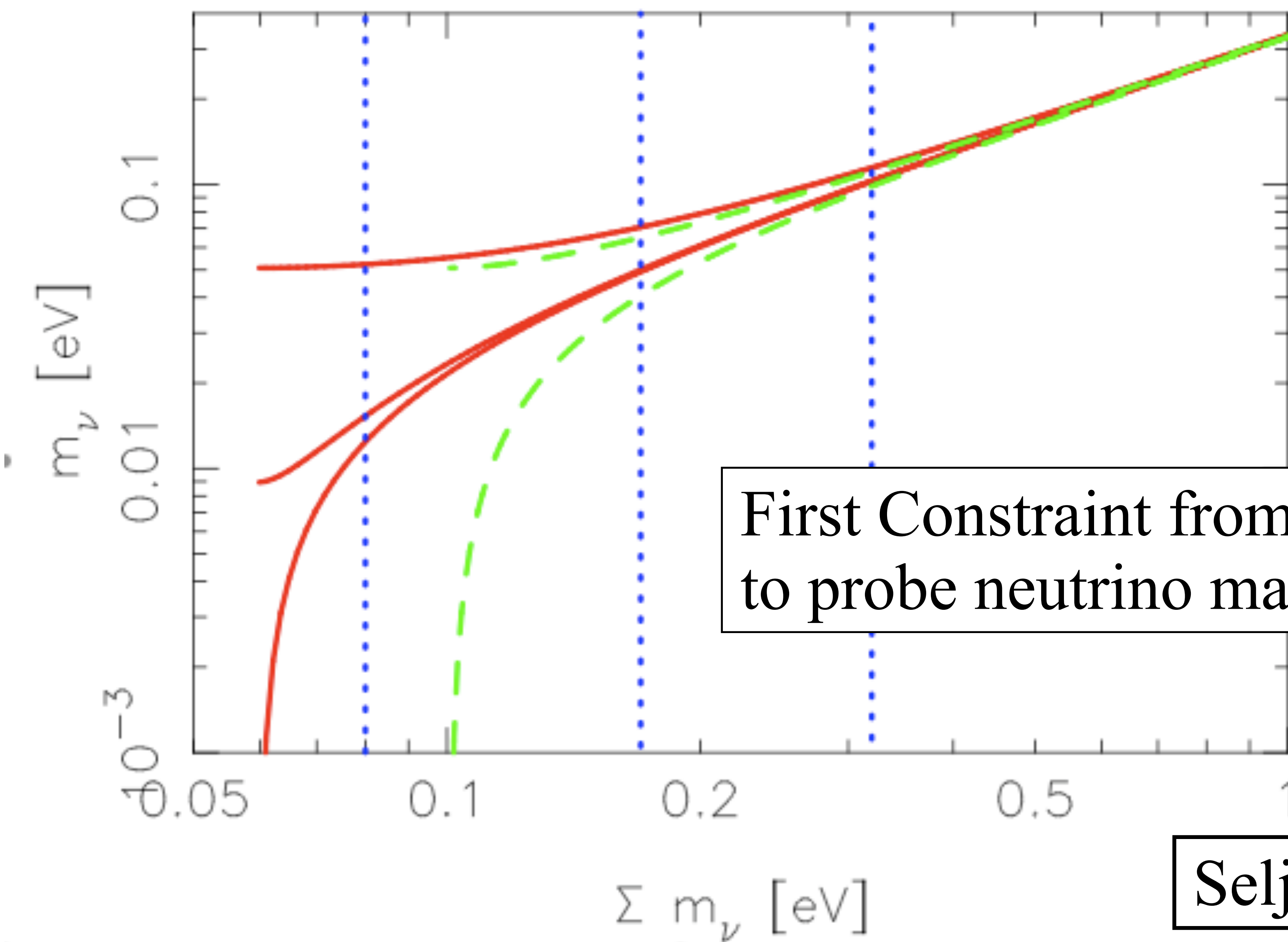
FIG. 2: The cross-correlation coefficient between the flux in our low and high resolution boxes, $\sqrt{\xi_{lh}^2/\xi_{ll}\xi_{hh}}$. Red points show the result for the two low resolution boxes having twice the smoothing length of the high resolution box, blue is the same for 4× smoothing length.



$P_\times(k)\ \times 1000$
$r_\perp = 20.0\mathrm{Mpc}/h$
$r_\perp = 28.3\mathrm{Mpc}/h$
$r_\perp = 40.0\mathrm{Mpc}/h$
$r_\perp = 44.7\mathrm{Mpc}/h$
$r_\perp = 56.6\mathrm{Mpc}/h$
$r_\perp = 60.0\mathrm{Mpc}/h$
$k[h/\mathrm{Mpc}]$

Lyman Alpha Forest: what can it do?

- **Cosmological Constraints from Lyman-alpha power spectrum**



First Constraint from Ly-alpha forest to probe neutrino masses

Seljak et al. 2006

Lyman Alpha Forest: what can it do?

- **Cosmological constraints from Lyman-alpha power spectrum (with no BAO)**

	Planck	Planck + BigBOSS Lya	Planck + BigBOSS Lya + Galaxies
$\sigma(\sum m_\nu)$	0.307	0.048	0.006
$\sigma(\Omega_K)$	0.011	0.0041	0.00038
$\sigma(n_s)$	0.0034	0.0023	0.001
$\sigma(dn_s/dln(k))$	0.003	0.0028	0.0005

Courtesy from Anze Slosar

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  - —Lyman-alpha power spectrum
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Lyman Alpha Forest: what can it do?
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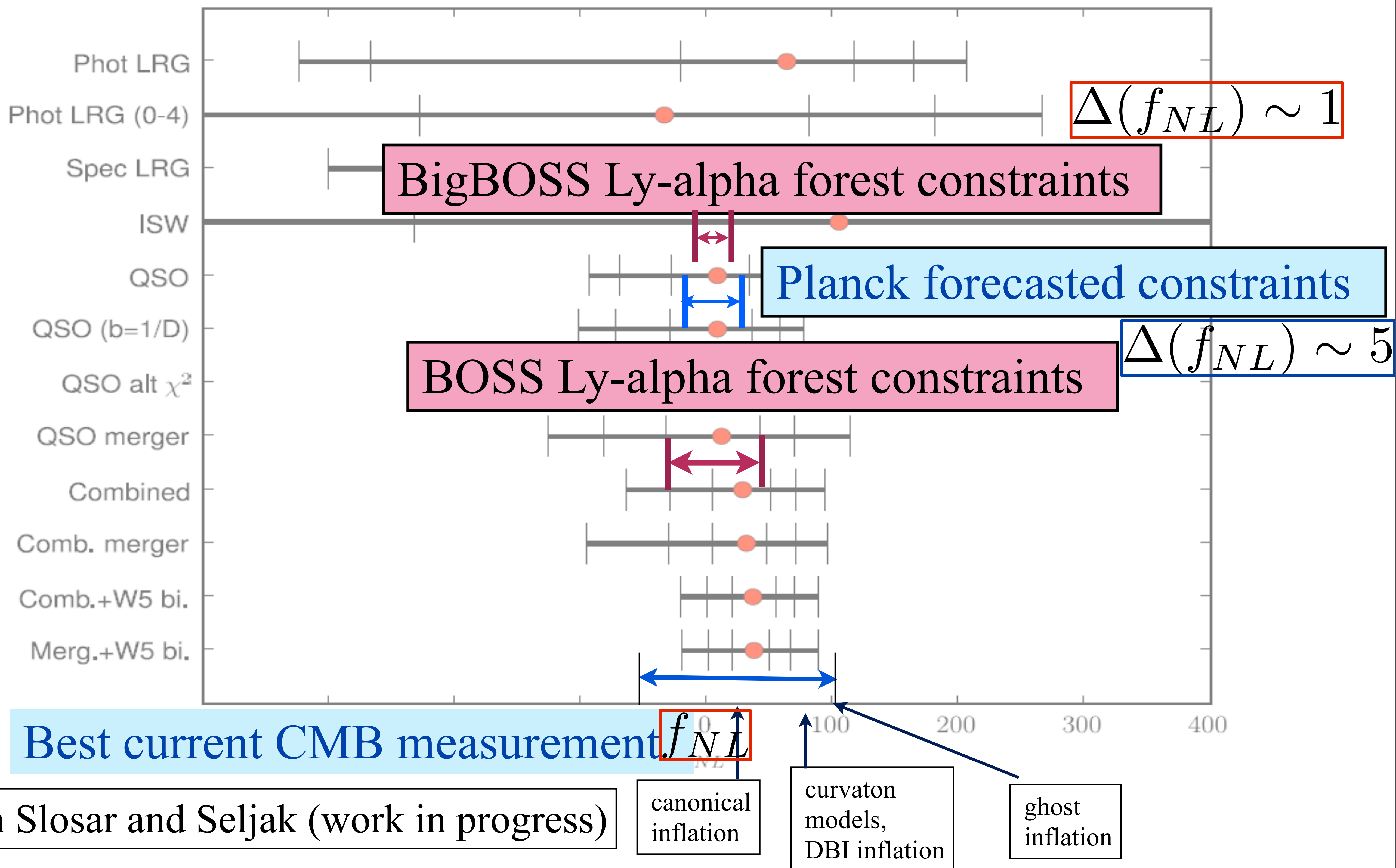

with Slosar and Seljak (work in progress)

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Lyman Alpha Forest: what can it do?

- **Simulation boxes of Dark matter**
- 3000^3 particles

  3000^3 mesh

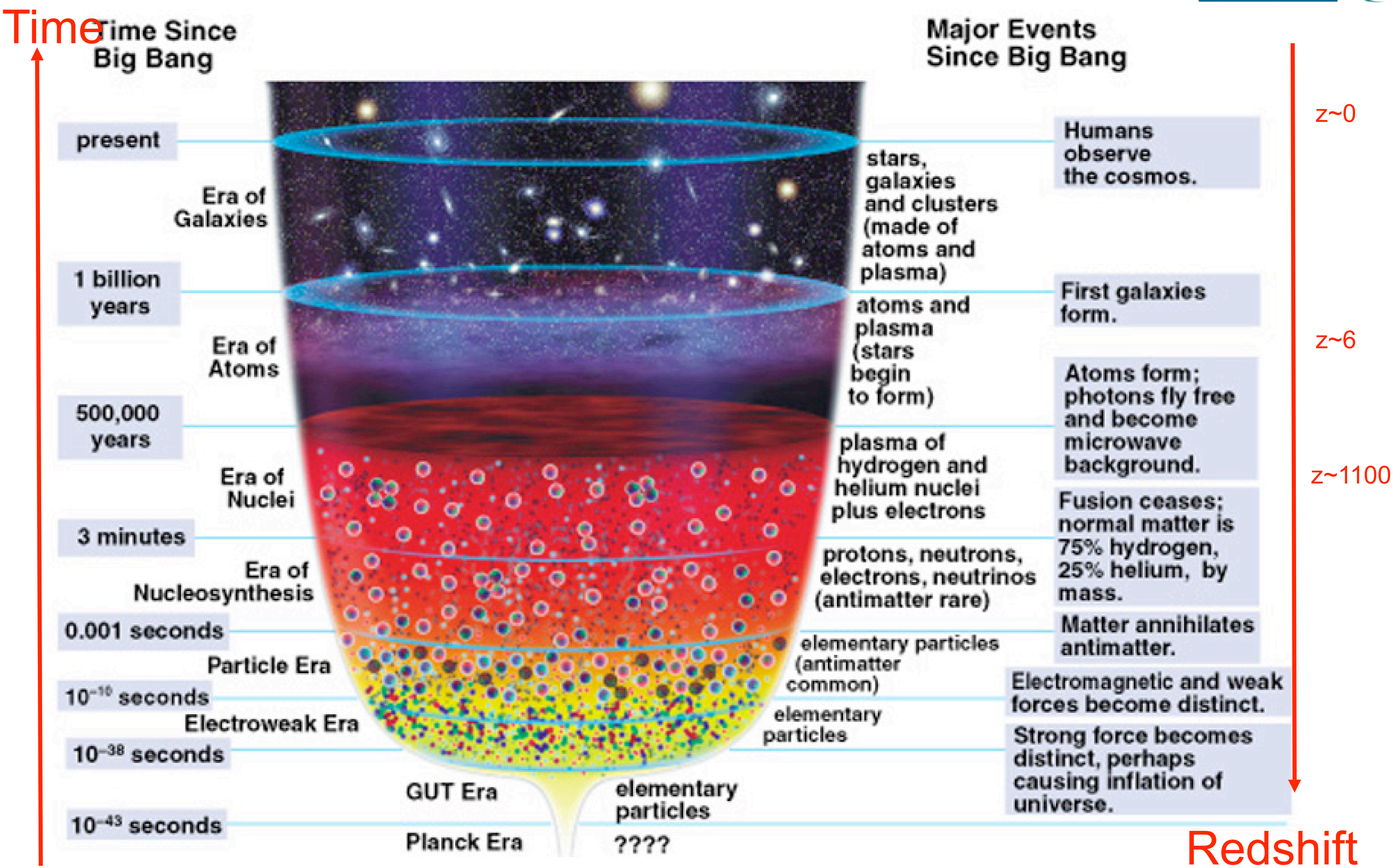
  $1500\ (h^{-1}Mpc)^3$ on the side

  $\Omega_m = 0.25,\ \Omega_\Lambda = 0.75,\ \mathrm{h} = 0.75,\ \mathrm{n} = 0.97,\ \sigma_8 = 0.8$

  Fluctuating Gunn Peterson approximation

  Peculiar velocities included

Motivations



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